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VALUE OF COKE, ANTHRACITE, AND BITUMINOUS COAL FOR GENERATING STEAM IN A LOW-PRESSURE CAST-IRON BOILER

By

JOHN BLIZARD, JAMES NEIL,
AND F. C. HOUGHTEN

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VALUE OF COKE, ANTHRACITE, AND BITUMINOUS COAL FOR GENERATING STEAM IN A LOW-PRESSURE CAST-IRON BOILER.

By JOHN BLIZARD, JAMES NEIL, AND F. C. HOUGHTEN.

INTRODUCTION.

Since its establishment the Bureau of Mines has been making tests and investigations relating to the increase of efficiency in utilizing fuels for the production of steam. The tests described in this paper were made by members of the Pittsburgh experiment station of the bureau.

The value of a fuel for the generation of steam depends chiefly on the total heat content of the fuel, and the thermal efficiency of the boiler. The boiler efficiency varies with the rate of steaming, method of firing, manipulation of the ash pit, fire door, and stack dampers, available draft, composition of the fuel, and construction of the boiler.

The boiler used during these tests was suitable for heating a large building. In most buildings it would probably be fired irregularly with fairly large quantities of coal, and the fireman most likely would have no draft gages, carbon dioxide recorder, or flue-gas thermometer to guide him in burning the coal with highest efficiency. In the tests reported here, the boiler was fired with 150-pound charges of fuel; the intervals between each firing were decreased as the rate of steaming increased; and the ash pit, fire door, and stack dampers were regulated—after observation of the gas analyses and temperatures—to burn the coal with the smallest heat loss. The thermal efficiency in these tests were therefore higher than they would be in the average plant.

The method of firing each fuel and operating the boiler was the same during all of the tests except five. In two of these bituminous coal was charged onto the front of the grate after part of the fuel bed had been pushed to the back of the grate; in two others more air was permitted to enter the furnace than might have been considered desirable for highest thermal efficiency; and during the remaining test the area of the grate was reduced.

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The H. B. Smith Co., of Westfield, Mass., lent the Bureau of Mines the boiler used. The following men assisted at various times in carrying out the tests: W. M. Myler, jr., R. F. Lunger, A. Pincus, A. L. Miller, W. T. Askin, J. K. Seabright, J. P. Stein, C. Schramm, J. F. Gardiner, J. J. McKitterick, H. Levison, B. K. Shanor, and H. Font. The composition and calorific value of the coal, the combustible content of the ash and refuse, and the composition of the special samples of gas were determined in the chemical laboratory under the direction of A. C. Fieldner.

PRINCIPAL RESULTS OF TESTS.

The complete results and comments thereon are recorded on later pages, but the outstanding features may be summarized briefly as follows:

Tests were made at different rates of steaming with coke, anthracite, and bituminous coal. Two tests also were run with a mixture of equal weights of bituminous coal and fairly coarse coke breeze, and two more with a mixture of equal weights of bituminous coal and a finer coke breeze. The calorific value of the coke ranged from 10,700 to 11,900 B. t. u. per pound; of the anthracite from 11,700 to 13,300 B. t. u., of the bituminous coal from 12,900 to 13,900 B. t. u.; and of the coke breeze-bituminous coal mixture from 11,200 to 11,800 B. t. u. The bituminous coal contained less ash than the coke or anthracite, about the same proportion of moisture, and, of course, far more volatile matter.

The mean steaming values of the coke, anthracite, and bituminous coals were about the same. At the low rate of steaming, the coke and anthracite evaporated more water than the bituminous coal, and at the higher rates of steaming the bituminous coal evaporated more water than the coke or the anthracite. The steaming value of the mixture of the coarser coke breeze and bituminous coal was about 80 per cent of that of bituminous coal alone, whereas the mean steaming value of the mixture of finer coke breeze and bituminous coal was lower than that of the mixture of coarser coke breeze.

When anthracite or coke was burned the thermal efficiencies were very high at the low rate of steaming, and fairly high at the high rate of steaming. They ranged between 79 and 66 per cent with coke, and between 77 and 66 per cent with anthracite. The main reason for the slightly lower mean efficiency with anthracite than with coke was that ash and refuse removed from the anthracite fire contained more combustible. The thermal efficiencies when burning bituminous coal ranged between 65 and 69 per cent. They varied little as the rate of steaming varied because as the rate of steaming

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increased the excess air decreased, which so offset the loss due to the higher flue-gas temperatures that the sensible heat in the flue gas increased but little, and because the percentage radiation loss, and loss through carbon monoxide was less at the higher rates of steaming. The thermal efficiency with bituminous coal at the lower ratings was less than the efficiencies with coke and anthracite, partly because the flue-gas temperature was considerably higher when bituminous coal was burned, and partly because this coal contained more hydrogen, which increased the heat content of the flue gases, owing to the total heat of the steam present in them, formed by burning hydrogen and evaporating moisture in the coal.

The high flue-gas temperatures while bituminous coal was burned were caused by the length of time required for burning the combustible gases, tars, and soot leaving the fuel bed, so that when they had burned the products of their combustion traveled a shorter distance to the stack, and therefore were unable to give up as much heat as they would have had they burned earlier in their path.

It is essential, therefore, when designing a boiler to burn bituminous coal, to arrange it not only to burn the gases completely but as rapidly as possible.

At the higher rates of steaming it was possible to burn the bituminous coal so that the flue gases contained little carbon monoxide and less free oxygen than when coke or anthracite was burned. When the free oxygen in the flue gas was increased by drawing more air into the furnace, so that the excess air increased from 40 to 100 per cent, combustion of the gases and tar in the furnace and combustion chamber was hastened, the flue-gas temperature lowered, and the thermal efficiency slightly increased. This reduction of flue-gas temperature with an increase of excess air was observed only when bituminous coal was burned with a comparatively small excess of air. When the excess air in the flue gases from anthracite or coke was increased above 100 per cent, the flue-gas temperature rose and the thermal efficiency fell.

When the mixture of bituminous coal and coke breeze was burned, the thermal efficiencies ranged from 57 to 65 per cent, and were less than those with the other fuels, mainly because the excess air on all tests, except one, was higher than in burning the other fuels.

PURPOSE OF THE TESTS.

The primary purpose of the tests was to determine the relative steaming values of coke, anthracite, and bituminous coal when burned in a low-pressure boiler, and fired by hand in fairly large quantities at a time.

A secondary purpose of the tests was to separate the heat losses, and to examine them carefully to determine the change in efficiency

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with the method of firing the fuel and manipulation of the draft dampers, with the rate of evaporation, and with the various fuels burned.

Other purposes may be mentioned, such as determination of the draft used, temperatures and composition of the gases in the flues, furnace, and combustion chamber, and other factors affecting the operation of the boiler.

Before these tests were completed, some special tests were run at the request of the Chamber of Commerce of Pittsburgh, to compare the steaming value and smoke emission of mixtures of coke breeze and Pittsburgh coal with those of the latter alone; results of these tests are also embodied in this report.

METHOD OF CONDUCTING TESTS.

All of the steam from the boiler passed to the atmosphere through an orifice box, at the outlet from which was an aperture, 3½, 3, 2½, or 1¾ inches diameter, depending on the desired rate of evaporation. The pressure in this box was kept as close as possible to 2 pounds per square inch above the pressure of the atmosphere, by opening or closing dampers to increase or decrease the rate of combustion of the fuel and the corresponding rate of evaporation. Tests were run with coke, anthracite, and bituminous coal at each of the rates of steaming, corresponding to the rates of flow under a pressure drop of 2 pounds per square inch through each of the four orifices, or at approximately 100, 80, 50, and 30 per cent, respectively, of the rated capacity of the boiler.

Approximately 6,000 pounds of fuel was fired during each test except two, one in which the grate-area was reduced; and another (coke breeze mixed with bituminous coal) that was curtailed by the warping of the grate-bars, which were not designed for coke breeze. Throughout the series of complete tests, 150 pounds of coal was charged at each firing, except rarely when it was necessary to fire a little more than that quantity. The intervals between firing varied with the rate of steaming; at the lowest rate the interval was about 85 minutes and at the highest rate about 20 minutes.

When fired, the fuel was spread over the whole grate in each test except two, in which after the upper part of the fuel-bed was pushed to the back of the grate, bituminous coal was fired on the front half of the grate only; that is to say, it was fired by the coking method.

All the coal used was weighed, and the test started and stopped with a fairly thin fuel-bed, which, as nearly as could be judged, contained the same quantity of fuel. A sample of fuel was taken for analysis during each test.

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The ash and refuse removed from above and below the grate were weighed, mixed, and then sampled for analysis.

The water fed to the boiler was weighed; the feed tank was calibrated to show its water content at any depth, and the boiler gage-glass was calibrated to show the quantity of water therein.

The wet steam leaving the boiler passed through a steam separator, and the water removed from the wet steam was weighed. The steam leaving the separator was assumed to be dry saturated steam. On no test did the water separated exceed 2 per cent of that fed to the boiler.

The steam pressure, feed-water temperature, and draft, air, and flue-gas temperatures were read every 15 minutes during the tests.

The draft, or difference between the pressure of the gases inside the boiler and air at the same altitude outside, was measured by observing the distance between the menisci of gasoline in a U-tube, which could be inclined to read to one one-thousandth of an inch of water. In all tests, measurements were made in the ash-pit, furnace, and the flue leaving the boiler and in some tests at additional points in the path of the gases between the furnace and flue.

To measure the flue-gas temperatures three exposed copper and constantan thermocouples of 22-gage wire were placed in the flue where the gases left the boiler. The difference between the e. m. f. of the hot and cold junctions was read by means of a potentiometer. Other special temperatures of the products of combustion were read during some of the tests with copper and constantan, chromel and alumel, and platinum and platinum-rhodium thermocouples, and a potentiometer.

PARTICULARS OF BOILER.

The boiler is a cast-iron, sectional type, known as the "No. 60," with the following dimensions:

Dimensions of boiler.

Length of grate, inches	[1] 78
Width of grate, inches	60
Area of grate, square feet	32.5
Area of heating surface, square feet	815
Ratio of heating surface to grate area	25
Steam rating, square feet of radiation	15,600
Steam rating, 1,000 B. t. u. per hour	3,780
Volume of mixing chamber, cubic feet	20
Volume of combustion chamber, cubic feet	36
Volume of furnace, cubic feet	93
Height from grate to roof of furnace, inches	32
Total number of sections	20
Length of foundation, inches	121
Total length of boiler, inches	158

[1] One test (No. 17) was run with the grate length reduced to 42 inches, but with the full width of 60 inches.

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Width at foundation, inches	72
Width of boiler, inches	98
Height of boiler, inches	87
Height of water line, inches	66
Height of ash pit, inches	18
Length of grate bars (double), inches	60
Distance between centers of grate bars, inches	6
Diameter of supply drum, inches	21
Diameter of return drums, inches	8
Distance from floor to smoke-pipe opening, inches	41
Size of smoke-pipe opening (oval), inches	16 by 37
Area of smoke-pipe opening, square feet	3.7
Total area of openings, furnace to mixing chamber, square feet	4
Asbestos covering, inches	2

During tests 1, 2, 3, 4, 5, 9, 10, 11, 13, 16, 17, and 1 SA, the coal was burned on shaking grate bars, with air spaces ½ inch wide, occupying 52 per cent of the total grate area.

These grate bars warped when burning a mixture of coke breeze, and were replaced by the makers of the boiler for tests 2, 3, and 4 SA; 7A, 8, 8A, 14, 14A, and 15, by stationary grate bars with ¼-inch air space, occupying 31 per cent of the total grate area.

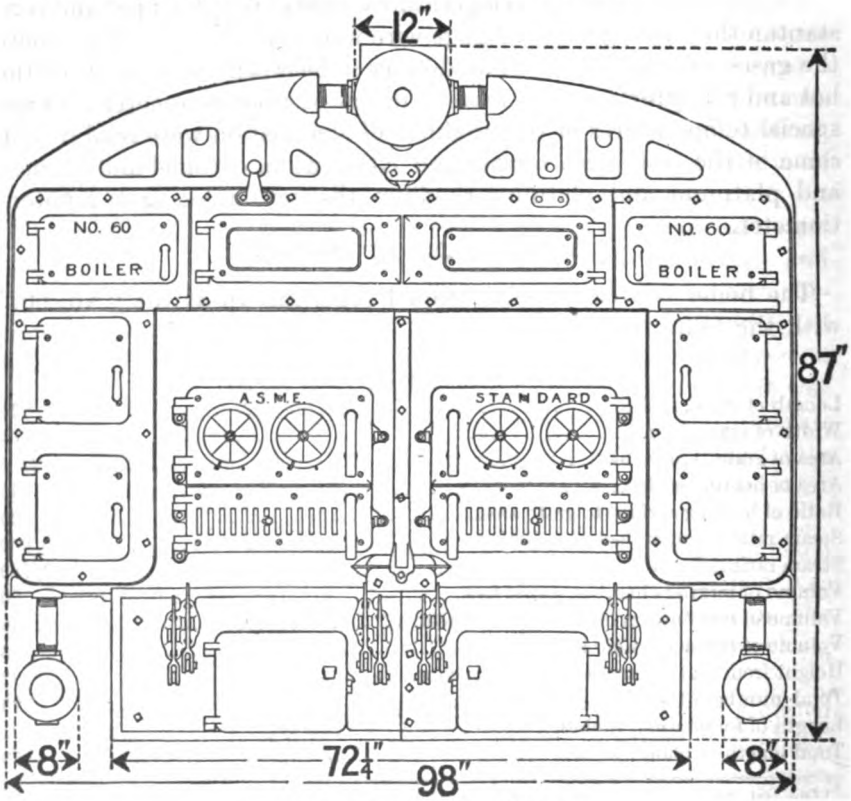

FIGURE 1.—Front view of boiler.

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Figure 1 shows a front view of the boiler, with the eight doors to obtain access to the flues, and the two fire doors and two ash-pit doors. Each fire door was made in two separate—upper and lower—parts, and each had adjustable openings through which air might pass to burn the combustible gases rising from the fuel bed. The total area of these air openings was 121 square inches.

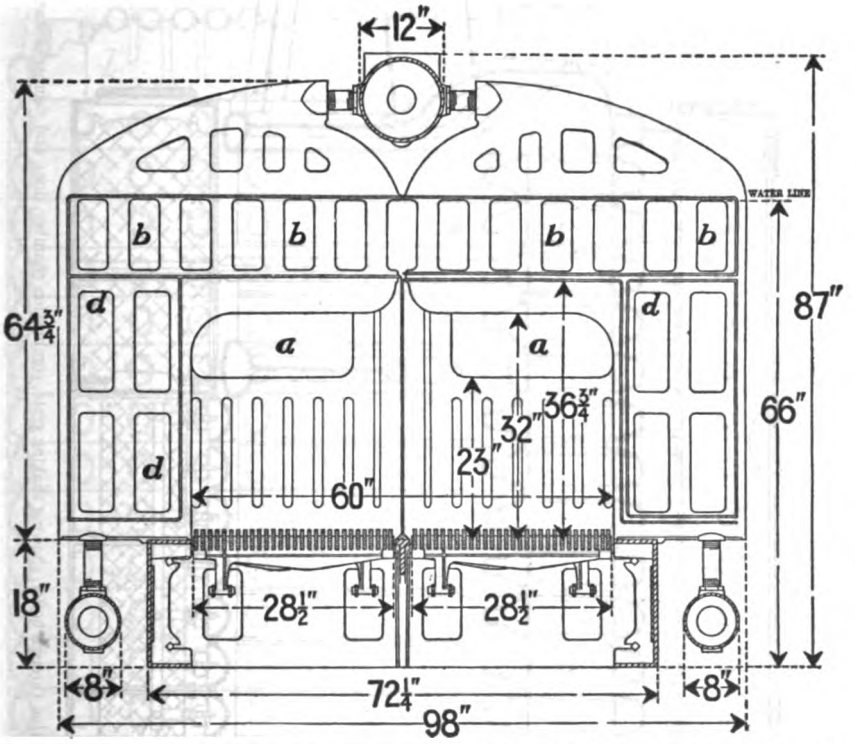

FIG. 2.—Transverse vertical section through furnace: *a*, openings in fireback to mixing chamber; *b*, openings from combustion chamber to front; *d*, openings from front to stack at back.

Figure 2 shows a transverse vertical section through the furnace; Figure 3 shows a longitudinal vertical section through the boiler; and Figure 4 a horizontal section through the top flues.

Each side of the boiler was composed of 20 cast-iron sections, each connected by one nipple to a water drum and by another to the steam drum. Joints between these sections were made with cement, so as to keep the gases flowing in the required path through the boiler.

The gases left the boiler furnace through two openings, *a* (Figs. 2 and 3), in the fireback section, passed into a mixing chamber, *m*, and thence through a vertical slot about 9 inches wide extending to the top of the mixing chamber from the floor, and into the combustion chamber *c*. From the mixing chamber they flowed up the top pass

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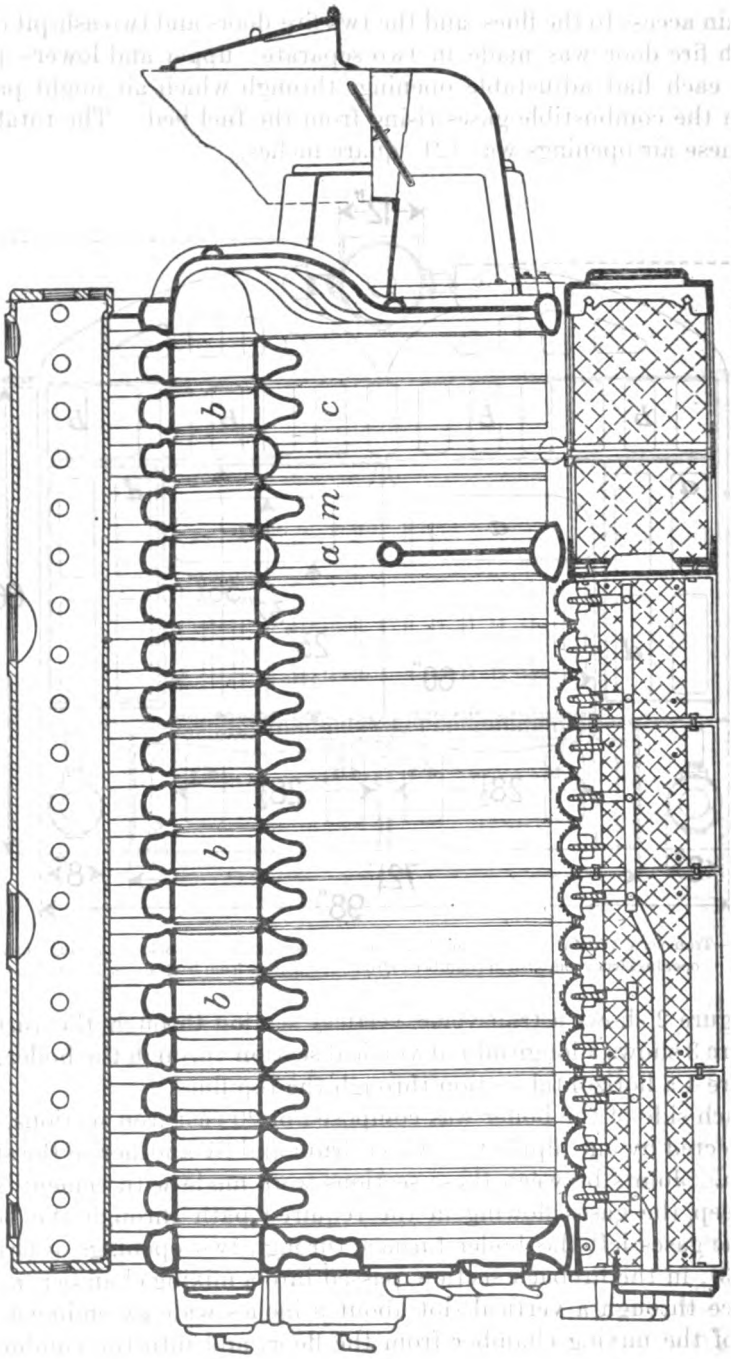

FIG. 3.—Longitudinal vertical section through boiler, showing shaking grate, combustion chamber, flues, and damper at stack.

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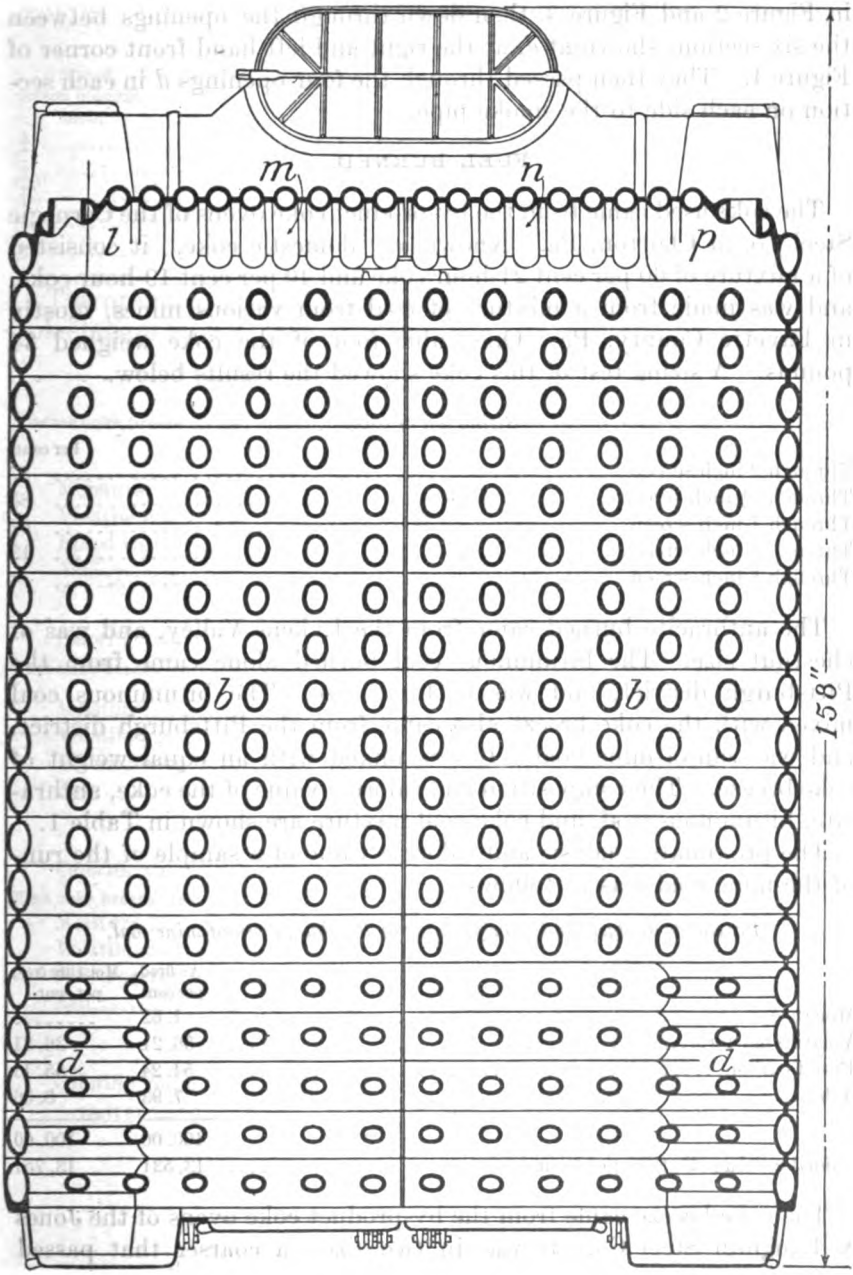

FIG. 4.—Section of boiler through top flues. Gases rising from combustion chamber flowed through openings at the back, forward through passages *b*, and descended through openings *d*, at front, to bottom pass.

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and moved towards the front of the boiler through the flues marked *b* in Figure 2 and Figure 3, then down through the openings between the six sections shown at *d*, at the right and left hand front corner of Figure 4. They then passed through the four openings *d* in each section on each side to the smoke pipe.

FUEL BURNED.

The coke used came from the by-product coke ovens of the Carnegie Steel Co. at Clairton, Pa. Known as "domestic coke," it consisted of a mixture of 60 per cent 21-hour coke and 40 per cent 19-hour coke, and was made from a mixture of coal from various mines, mostly in Fayette County, Pa. One cubic foot of the coke weighed 34 pounds. A sizing test of this coke showed the results below.

Sizing test of coke.

	Per cent.
Through 2-inch screen	87
Through 1½-inch screen	85
Through 1-inch screen	62
Through ½-inch screen	13
Through ¼-inch screen	4

The anthracite burned came from the Lykens Valley, and was of chestnut size. The bituminous coal burned alone came from the Pittsburgh district, and was of lump size. The bituminous coal mixed with the coke breeze also came from the Pittsburgh district, and was run-of-mine coal. It was mixed with an equal weight of coke breeze. The composition and calorific value of the coke, anthracite, bituminous coal, and coke-coal mixture are shown in Table 1.

The proximate analysis and calorific value of a sample of the run-of-the-mine coal was as follows:

Proximate analysis and calorific value of Pittsburgh run-of-mine coal.

	As fired, per cent.	Moisture free, per cent.
Moisture	1.62	.....
Volatile matter	36.21	36.81
Fixed carbon	54.24	55.13
Ash	7.93	8.06
	100.00	100.00
Calorific value (B. t. u. per pound)	13,531	13,754

The coke breeze came from the by-product coke ovens of the Jones & Laughlin Steel Co. It was in two sizes, a coarser that passed

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through a ¾ to 1 inch screen and a finer that passed through a ½-inch screen. The size of the particles was as shown below:

Sizing test of coke breeze.

Size of screen opening, inch.	Coarse, per cent through.	Fine, per cent through.
¾	78	...
½	67	100
¼	50	78
1/10	33	60
1/30	11	9

The proximate analysis and calorific value of three samples of the coke breeze were as follows:

Proximate analyses and heating value of coke breeze.

	As fired, per cent.	Moisture free, per cent.
Coarse coke breeze (tests 1 and 2):		
Moisture	7.39	.....
Volatile matter	2.49	2.69
Fixed carbon	66.35	71.64
Ash	23.77	25.67
	100.00	100.00
Calorific value (B. t. u. per pound)	9,748	10,526
Fine coke breeze (test 3):	As fired.	Moisture free.
Moisture	6.55	.....
Volatile matter	3.40	3.64
Fixed carbon	65.01	69.56
Ash	25.04	26.80
	100.00	100.00
Calorific value (B. t. u. per pound)	9,559	10,229
Fine coke breeze (test 4):		
Moisture	4.01	.....
Volatile matter	3.04	3.17
Fixed carbon	66.25	69.01
Ash	26.70	27.82
	100.00	100.00
Calorific value (B. t. u. per pound)	9,995	10,413

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TABLE 1.—*Results of tests.*

Reference No.	General particulars.	Units.	Coke.					Anthracite.				
1	Number of trial		1	2	3	14	14A	4	5	7A	8	8A
2	Duration of trial	Hours	59.42	30.58	18.42	12.00	11.10	55.25	27.25	24.67	15.33	12.33
3	Average interval between firings	Minutes	85	44	25	18	18	85	40	40	24	20
	Fuel:											
	Ultimate analysis as fired—											
4	Hydrogen	Per cent	0.99	1.00	1.00	0.91	1.17	2.59	2.63	2.68	2.83	2.60
5	Carbon	do	77.57	79.50	79.05	75.45	71.29	73.92	76.17	77.82	82.08	74.87
6	Nitrogen	do	1.27	1.29	1.29	1.19	1.13	0.81	0.84	0.75	0.78	0.84
7	Oxygen	do	2.21	2.16	2.24	1.76	3.95	5.18	5.03	3.68	3.94	4.67
8	Sulphur	do	0.88	1.00	0.94	0.98	0.97	1.00	1.25	0.86	0.60	0.98
9	Ash	do	17.08	15.05	15.48	19.71	21.49	16.50	14.08	14.21	9.77	16.04
	Proximate analysis as fired—											
10	Moisture	do	1.78	1.73	1.80	1.30	2.53	3.08	2.85	1.95	2.12	3.02
11	Volatile matter	do	3.07	3.15	2.90	1.72	3.19	6.62	6.63	5.90	5.71	5.25
12	Fixed carbon	do	78.07	80.07	79.82	77.27	72.79	73.80	76.44	77.94	82.40	75.69
13	Ash	do	17.08	15.05	15.48	19.71	21.49	16.50	14.08	14.21	9.77	16.04
14	Fuel ratio F. C./V. M.		25.43	25.42	27.52	44.92	22.81	11.14	11.53	13.20	14.43	14.41
	Calorific value of fuel per pound—											
15	As fired	B. t. u	11,634	11,862	11,743	11,344	10,741	11,899	11,735	12,449	13,286	12,084
16	Dry	do	11,845	12,071	11,958	11,493	11,020	12,277	12,079	12,697	13,574	12,460
17	Moisture and ash free	do	14,338	14,255	14,195	14,361	14,137	14,795	14,126	14,849	15,079	14,929
18	Total fuel fired during trial	Pounds	6,400	6,350	6,450	6,150	6,000	6,400	6,450	6,050	5,900	6,000
	Ash and refuse:											
19	Total ash and refuse removed during trial	do	1,267	1,059	1,232	1,364	964	1,695	1,400	1,418	910	1,374
20	Carbonaceous matter in ash and refuse	Per cent	19.92	22.12	26.64	24.51	17.82	38.00	35.70	44.00	44.97	34.35
21	Ash and refuse removed, per cent fuel as fired	do	19.80	16.68	19.10	22.18	16.06	26.50	21.70	23.40	15.42	22.90
	Draft:											
22	In ash pit	Inches water	.024	.031	.007	.031	.028	.002	.002	.018	.006	.026
23	In furnace	do	.017	.034	.032	.120	.120	.014	.050	.102	.210	.228
24	In stack	do	.042	.116	.262	.720	.830	.041	.154	.310	.530	.900
	Air:											
25	Temperature air entering ash pit	°F	75	82	89	76	86	78	79	76	75	75
26	Excess air in flue gases	Per cent	75	97	85	102	129	98	95	133	79	112
	Flue gases:											
	Analysis dry flue gases by volume—											
27	Carbon dioxide	do	11.0	10.0	10.6	10.2	8.6	9.6	9.4	8.2	10.6	9.0
28	Oxygen	do	9.1	10.4	9.7	10.6	11.9	10.5	10.4	12.1	9.4	11.2
29	Carbon monoxide	do	0.2	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.1	0.1
30	Nitrogen (by difference)	do	79.7	79.6	79.7	79.2	79.5	79.8	80.2	79.6	79.9	79.7
31	Mean temperature flue gases leaving boiler	°F	278	347	447	554	619	272	368	410	537	529

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	Steam and feed water:											
32	Gage pressure, boiler	Pounds per square inch.	8	7	7	6	3	8	8	7	7	6
33	Temperature of feed water	°F	76	77	77	45	49	75	75	49	51	48
	Rates:											
34	Per cent of builder's rating	Per cent	26	50	80	113	101	28	54	58	89	102
35	Heat transferred to water per hour	1,000 B. t. u.	988	1,885	3,027	4,270	3,827	1,066	2,051	2,190	3,377	3,865
36	Heat transferred to water per square foot of heating surface per hour.	B. t. u.	1,210	2,310	3,710	5,240	4,690	1,310	2,520	2,685	4,134	4,742
37	Fuel fired per hour	Pounds	108	208	350	513	541	116	237	245	385	487
38	Fuel fired per square foot grate surface per hour	do	3.3	6.4	10.8	15.7	16.6	3.5	7.3	7.5	11.8	15.0
	Heat balance, per pound fuel as fired:											
39	Heat transferred to water	B. t. u	9,189	9,090	8,670	8,340	7,080	9,210	8,680	8,920	8,770	7,945
40	Heat carried away by steam in flue gases	do	101	104	110	104	136	260	279	290	322	296
41	Heat carried away by dry flue gases	do	816	1,250	1,495	2,025	2,560	800	1,270	1,678	2,025	2,115
42	Heat lost by not burning carbon monoxide	do	113	0	0	0	0	46	27	58	57	52
43	Heat lost by not burning carbonaceous matter from ash pit and grate.	do	578	536	740	790	414	1,460	1,110	1,495	1,006	1,142
44	Undetermined losses	do	840	880	720	85	557	101	376	8	1,106	534
45	Total and calorific value of fuel	do	11,634	11,862	11,743	11,344	10,741	11,899	11,735	12,449	13,286	12,084
	Heat balance, per cent heat in fuel as fired:											
46	Heat transferred to water (thermal efficiency)	Per cent	79.0	76.6	73.8	73.5	65.9	77.3	74.0	71.6	65.8	65.8
47	Heat carried away by steam in flue gases	do	0.9	0.9	0.9	0.9	1.3	2.2	2.4	2.3	2.4	2.5
48	Heat carried away by dry flue gases	do	7.0	10.5	12.7	17.9	23.8	6.7	10.8	13.5	15.3	17.5
49	Heat lost by not burning carbon monoxide	do	1.0	0.0	0.0	0.0	0.0	0.4	0.2	0.5	0.4	0.4
50	Heat lost by not burning carbonaceous matter from ash pit and grate.	do	5.0	4.5	6.3	7.0	3.8	12.3	9.4	12.0	7.5	9.5
51	Undetermined losses	do	7.1	7.5	6.3	0.7	5.2	1.1	3.2	0.1	8.6	4.3
52	Total	do	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

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TABLE 1.—*Results of tests*—Continued.

Reference No.	General particulars.	Units.	Bituminous coal.								Bituminous coal and coke breeze.			
			Spreading.						Coking.		Coarse grade.	Coarse grade.	Fine grade.	Fine grade.
1	Number of trial		12	17	9	10	11	16	15	13	1 S. A.	2 S. A.	4 S. A.	3 S. A.
2	Duration of trial	Hours	37.67	22.33	25.25	16.83	13.33	12.17	23.83	16.25	28.00	15.92	35.00	22.83
3	Average interval between firings	Minutes	61	51.5	39	25	20	18.6	40	25	54	25	53	36
	Fuel:													
	Ultimate analysis as fired—													
4	Hydrogen	Per cent	5.11	5.35	5.27	5.30	5.34	5.33	5.12	5.15	3.21	3.21	3.06	3.17
5	Carbon	do	72.25	72.30	77.71	77.22	77.94	73.08	72.54	74.54	68.76	68.76	70.58	68.55
6	Nitrogen	do	1.47	1.46	1.57	1.56	1.58	1.53	1.48	1.55	1.07	1.07	1.10	1.06
7	Oxygen	do	8.40	8.83	7.70	8.23	8.17	8.73	8.44	8.03	8.48	8.48	6.49	8.10
8	Sulphur	do	1.95	2.35	1.02	1.40	0.95	2.10	2.08	1.68	1.61	1.61	1.46	1.61
9	Ash	do	10.82	9.71	6.73	6.29	6.02	9.75	10.34	9.05	16.87	16.87	17.31	17.51
	Proximate analysis as fired—													
10	Moisture	do	2.14	2.42	1.70	2.34	2.22	2.25	2.13	1.90	5.21	5.21	2.81	4.79
11	Volatile matter	do	36.08	39.46	35.00	34.49	34.60	38.14	37.83	35.30	18.79	18.79	19.63	19.23
12	Fixed carbon	do	50.86	48.41	56.57	56.88	57.16	49.88	49.70	53.75	59.13	59.13	60.25	58.47
13	Ash	do	10.82	9.71	6.73	6.29	6.02	9.75	10.84	9.05	16.87	16.87	17.31	17.51
14	Fuel ratio F. C./V. M.		1.41	1.20	1.62	1.65	1.65	1.31	1.31	1.52	3.15	3.15	3.07	3.04
	Calorific value of fuel per pound—													
15	As fired	B. t. u.	12,906	13,001	13,867	13,838	13,940	13,116	12,984	13,337	11,307	11,307	11,763	11,213
16	Dry	do	13,188	13,323	14,107	14,170	14,256	13,418	13,267	13,595	11,897	11,897	12,084	11,749
17	Moisture and ash free	do	14,828	14,795	15,144	15,145	15,192	14,901	14,833	14,977	14,476	14,476	14,693	14,382
18	Total fuel fired during trial	Pounds	6,000	4,000	6,000	6,050	5,950	6,000	6,000	5,700	4,700	5,850	6,150	6,050
	Ash and refuse:													
19	Total ash and refuse removed during trial	do	628	365	506	511	636	506	755	590	1,066	1,120	1,588	1,646
20	Carbonaceous matter in ash and refuse	Per cent	21.84	15.24	22.52	30.97	44.89	19.24	21.10	39.07	31.94	20.09	36.66	28.49
21	Ash and refuse removed, per cent fuel as fired	do	10.47	9.12	8.43	8.45	10.69	8.43	12.58	10.35	22.66	19.13	25.80	27.20
	Draft:													
22	In ash pit	Inches water	.027	.030	.010	.017	.023	.006	.022	.020	.042	.005	.009	.007
23	In furnace	do	.039	.049	.016	.039	.052	.044	.054	.055	.089	.117	.080	.189
24	In stack	do	.133	.145	.200	.382	.499	.850	.238	.337	.220	.550	.183	.500
	Air:													
25	Temperature air entering ash pit	°F	78	74	83	88	88	89	74	82	75	78	75	74
26	Excess air in flue gases	Per cent	136	148	101	45	39	104	118	77	193	138	172	258
	Flue gases:													
	Analysis dry flue gases by volume—													
27	Carbon dioxide	do	7.1	6.8	8.0	11.9	11.7	8.5	8.0	9.2	6.5	7.8	6.7	5.2
28	Oxygen	do	12.3	12.7	10.8	6.6	6.1	10.9	11.5	9.4	13.9	12.3	13.4	15.2
29	Carbon monoxide	do	0.3	0.4	0.4	0.4	0.1	0.1	0.4	0.1	0.2	0.1	0.2	0.1
30	Nitrogen (by difference)	do	80.3	80.1	80.8	81.1	82.1	80.5	80.1	81.3	79.4	79.8	79.7	79.5
31	Mean temperature flue gases leaving boiler	°F	441	402	557	761	822	654	580	616	452	571	382	464

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	Steam and feed water:												
32	Gage pressure, boiler	Pounds per square inch.	9	8	6	8	5	4	7	6	5	4	8	5
33	Temperature of feed water	°F	44	58	75	76	75	57	46	74	53	50	50	50
	Rates:													
34	Per cent of builder's rating	Per cent	36	41	56	85	107	117	56	83	31	71	34	45
35	Heat transferred to water per hour	1,000 B. t. u.	1,370	1,540	2,127	3,227	4,025	4,430	2,133	3,148	1,184	2,694	1,272	1,700
36	Heat transferred to water per square foot of heating surface per hour.	B. t. u.	1,681	1,880	2,610	3,760	4,940	5,436	2,617	3,860	1,453	3,306	1,561	2,085
37	Fuel fired per hour	Pounds	159	179	238	360	446	493	252	350	168	368	176	265
38	Fuel fired per square foot grate surface per hour	do	4.9	10.2	7.5	11.1	13.8	15.2	7.7	10.8	5.2	11.3	5.4	8.2
	Heat balance, per pound fuel as fired:													
39	Heat transferred to water	B. t. u.	8,600	8,560	8,960	8,980	9,030	8,981	8,480	8,950	7,040	7,322	7,238	6,425
40	Heat carried away by steam in flue gases	do	560	578	603	645	660	627	593	600	354	369	327	350
41	Heat carried away by dry flue gases	do	2,140	1,948	2,490	2,533	2,660	2,854	2,661	2,418	2,284	2,533	1,645	2,800
42	Heat lost by not burning carbon monoxide	do	288	399	330	239	33	101	346	36	187	83	180	117
43	Heat lost by not burning carbonaceous matter from ash pit and grate.	do	332	202	280	379	695	235	384	595	1,058	555	1,382	1,130
44	Undetermined losses	do	1,244	1,314	1,204	1,062	862	318	520	738	384	445	991	391
45	Total and calorific value of fuel	do	12,906	13,001	13,867	13,838	13,940	13,116	12,984	13,337	11,307	11,307	11,763	11,213
	Heat balance, per cent heat in fuel as fired:													
46	Heat transferred to water (thermal efficiency)	Per cent	66.6	65.8	64.6	64.9	64.8	68.5	65.3	67.1	62.3	64.8	61.5	57.3
47	Heat carried away by steam in flue gases	do	4.3	4.4	4.3	4.7	4.8	4.8	4.6	4.5	3.1	3.3	2.8	3.1
48	Heat carried away by dry flue gases	do	16.6	15.0	17.9	18.3	19.1	21.7	20.5	18.1	20.2	22.4	14.0	25.0
49	Heat lost by not burning carbon monoxide	do	2.2	3.1	2.4	1.7	0.2	0.8	2.7	0.3	1.6	0.7	1.5	1.0
50	Heat lost by not burning carbonaceous matter from ash pit and grate.	do	2.6	1.6	2.0	2.7	5.0	1.8	3.0	4.5	9.4	4.9	11.8	10.1
51	Undetermined losses	do	7.7	10.1	8.8	7.7	6.1	2.4	3.9	5.5	3.4	3.9	8.4	3.5
52	Total	do	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

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DISCUSSION OF RESULTS OF TESTS.

Table 1 shows the principal results of the tests, grouped so that tests made at higher ratings follow those at lower ratings for the same fuel and method of firing.

Four normal tests (1, 2, 3, and 14) were run with coke, five normal tests (4, 5, 7A, 8, and 8A) with anthracite, four normal tests (12, 9, 10, and 11) with bituminous coal, and four with the mixtures of bituminous coal and coke breeze. During the normal tests the fuel was spread over the whole of the grate, and the dampers were adjusted to obtain the highest carbon dioxide content in the flue gas, with little or no carbon monoxide.

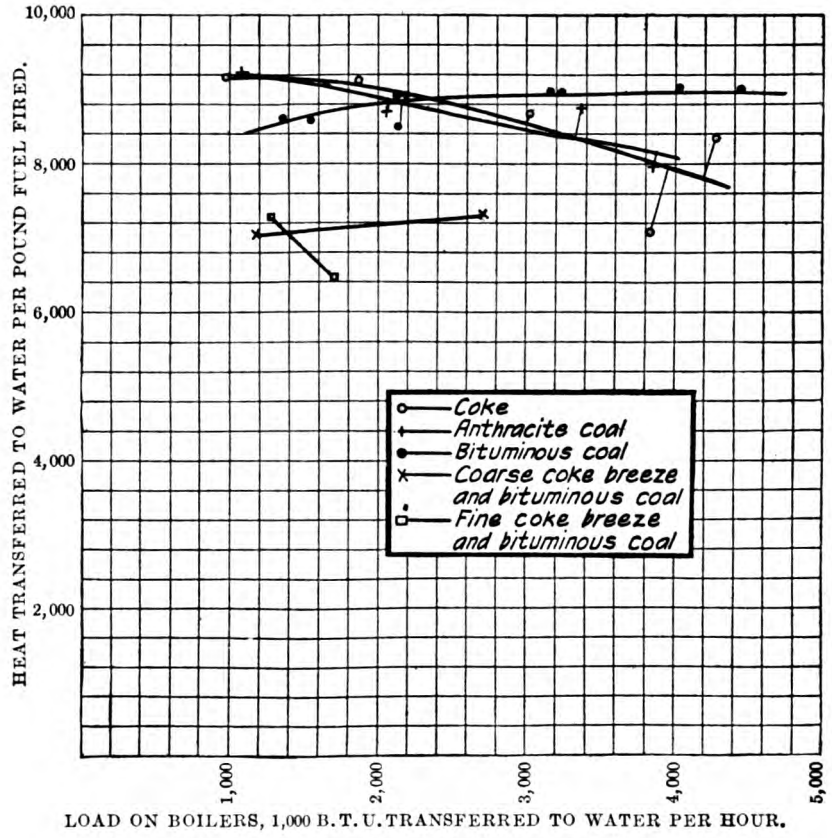

FIG. 5.—Relative steaming value of fuels tested.

An additional coke test (14A) was made with less carbon dioxide in the flue gas than during the other tests with coke.

Four special tests were made with bituminous coal, one (17) with a reduced grate area, at a low rate of steaming, two (15 and 13) with the coal fired by the coking method, and another (16) with an increased air supply above the fuel bed.

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COMPARATIVE STEAMING VALUE OF FUELS.

As the calorific value of the coke, anthracite bituminous coal, and coke breeze differed in each test, and as the efficiency varied with the rate of steaming, it is impossible to give an exact figure that compares as a whole the relative steaming values of the fuels. The steaming value, or useful effect, of each fuel for each test is shown on line 39, Table 1, which gives the net quantity of heat transferred to the water in the boiler per pound of fuel fired. The mean steaming values at different rates of steaming are shown graphically in Figure 5 by the perpendicular distance from points on the curves to the base line of the chart.

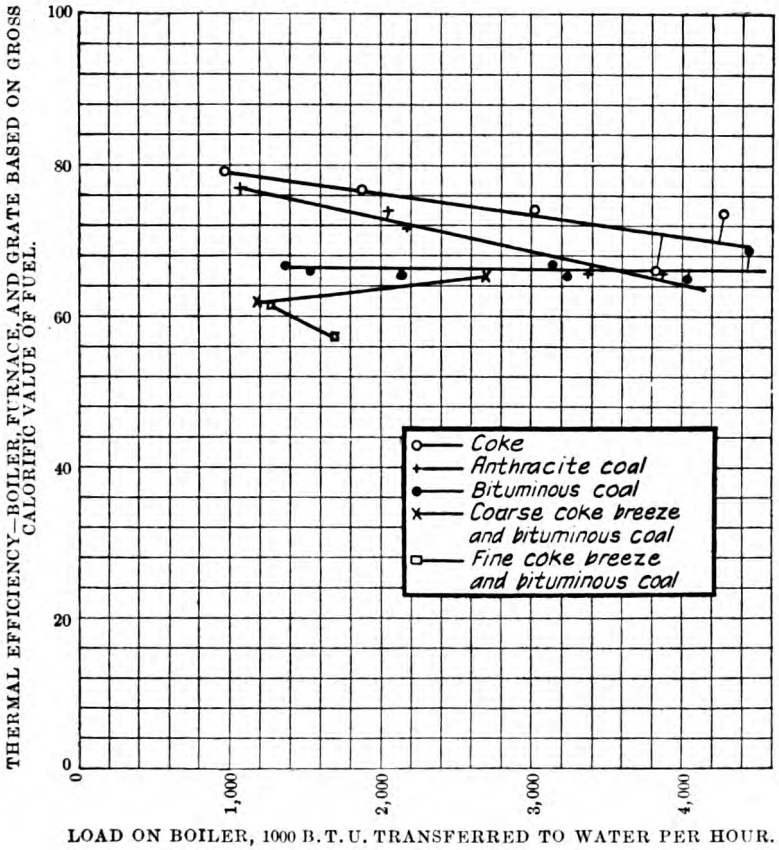

FIG. 6.—Over-all thermal efficiencies at different rates of steaming.

This chart shows that at about one-half of the maker's rating the quantities of steam generated by equal weights of coke, bituminous coal, and anthracite were about the same. At higher rates of steaming, the steam generated per pound of bituminous coal exceeded that generated by the anthracite and coke, but at the lower rate it was less. The mean steaming values of the coke and anthracite are about the same, and the steam generated by the mixtures of coke breeze and bituminous coal was less than that generated by the other fuels.

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THERMAL EFFICIENCY.

Line 46 of Table 1 gives the over-all thermal efficiency; below it are lines giving the heat losses; and Figure 6 presents the over-all thermal efficiencies at different rates of steaming, on a chart similar to that of Figure 5, showing the steaming values.

The efficiency of the coke is shown by a straight line, on which lie the three points to the left corresponding to the three lower rates of steaming. One of the two points joined to the right of the curve corresponds to test 14 and is above the line, because from inaccurate judging of the fuel bed the actual efficiency during this test was probably lower than that found, as the undetermined loss was very low. The other point joined to the right of the line, and lying below

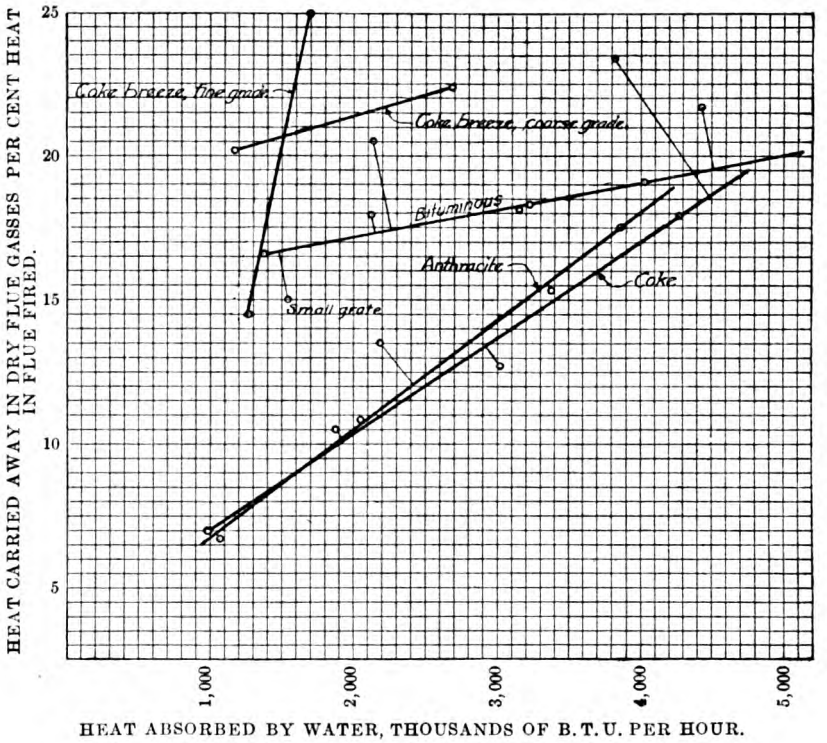

FIG. 7.—Heat carried away as sensible heat by dry flue gases at different rates of steaming.

it, corresponds to test 14A, and is shown well below the curve. The lower efficiency during test 14A was caused by a comparatively high excess of air in the flue gases. (See line 26 in Table 1.)

The anthracite efficiency is shown by a straight line that approaches the coke efficiency line to the left, and gradually recedes from it to the right at the higher rates of steaming.

The efficiency curve for coke lies well above that for anthracite, mainly because the heat lost by not burning the carbonaceous matter in the ash and refuse removed from the ash pit and grate was less

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(line 50, Table 1), and partly because the coke contained less hydrogen, which made the loss due to steam in the flue gases a little over 1 per cent less; and also partly because the dry flue-gas loss at the higher rates of steaming was less (Fig. 7).

The efficiency with bituminous coal as fuel is shown by a straight line, corresponding to an almost constant efficiency of 66 per cent. This line lies below the anthracite line to the left, and cuts it on the right. To account for the practically constant efficiency, Figure 8 has been prepared, which shows the thermal efficiencies and the various losses, as percentages of the heat in the coal. At the top

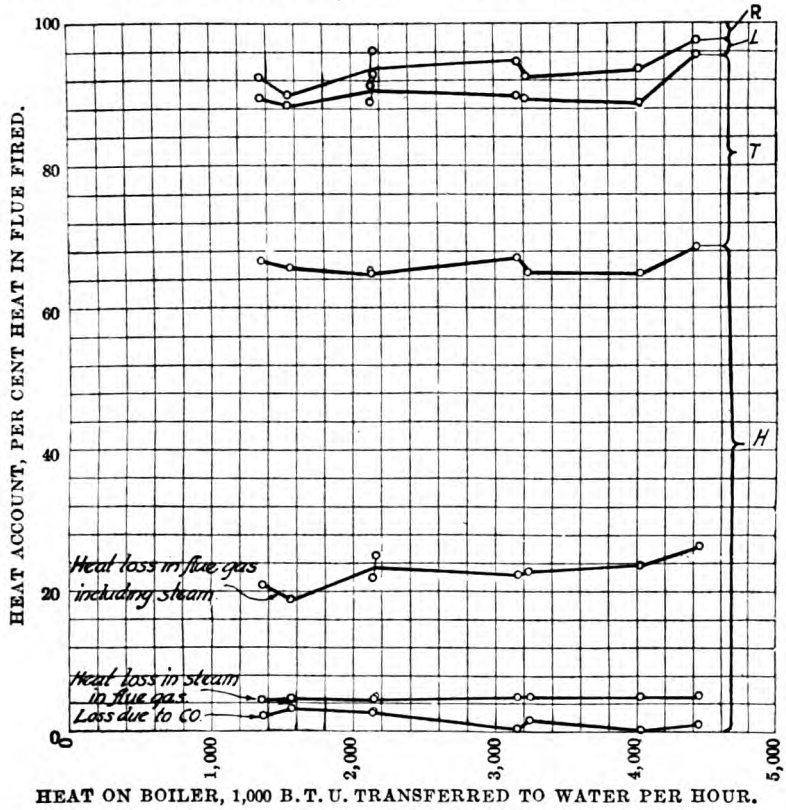

FIG. 8.—Heat account of of bituminous coal at different rates of steaming: *R*, Radiation, unaccounted for; *L*, carbonaceous matter in ash loss; *T*, heat content of total flue gases; *H*, thermal efficiency.

is shown "the radiation loss and errors," which is represented by the distance between the top curved line and the line, drawn perpendicular to the ordinates, through 100. These distances tend to decrease as the rating increases, because the heat lost by radiation per unit of time increases less rapidly with the load than the heat liberated by burning the coal to maintain the load. In these undetermined losses are included those caused by tar, soot, and hydrocarbons in the gases leaving the boiler; the somewhat inconsistent

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shape of this curve must be due partly to the relative quantities of tar and soot in the flue gases during the various tests.

The distances between the upper curved line and the curved line immediately below it show the loss caused by carbonaceous matter in the ash. Below this space the total observed flue-gas loss is shown, which includes the losses due to the sensible heat in the flue gas, the latent heat of the steam in the flue gas, and the loss through carbon monoxide.

At the bottom of the chart are three curved lines: The distances from the base of the chart to the highest of these shows the total loss caused by the steam and dry flue gases, but does not include the loss attributed to carbon monoxide, which is shown separately at the bottom. The heat lost in the steam in the flue gas is also shown separately.

The chart shows that the losses caused by radiation and errors and carbon monoxide decrease as the rate of steaming increases, enough to offset the small increase in the heat loss of the flue gases as the rate of steaming increases, and accounts for the small change in the thermal efficiency with the load. This small increase of flue-gas loss with the rate of steaming with bituminous coal will be discussed later (p. 26).

Two special tests (13 and 15) were run with bituminous coal fired by the coking method. During No. 13 the efficiency was 67 per cent, or about 2 per cent higher than No. 10, which was run at practically the same rating, and fired by spreading the coal over the whole fuel bed at each firing. The heat account (items 46 to 52, Table 1 and Fig. 8) shows the losses caused by carbon monoxide and the unaccounted for losses to be higher, and the loss from carbon in the ash to be lower in No. 10 than in No. 13, but the other losses are practically the same; the higher efficiency for No. 13 is probably attributable to the loss in unburned gases and tars—undetermined by sampling and analysis—being less than in No. 10. This higher efficiency for No. 13 is not to be attributed to the coking method of firing, but to the admission of more air over the fuel bed, for during test 13, the flue gases contained 77 per cent excess air but only 45 per cent in test 10. It is astonishing to find that in spite of the greater excess air, the dry flue-gas loss was slightly less than in test 10, but the temperature of the flue gas was much lower in test 13 (616° F.) than in test 10 (761° F.), and evidently during test 13 the gases rising from the fuel bed burned more rapidly and earlier in their path to the stack, because of the larger air supply, and thus were able to transfer more heat to the boiler.

That the efficiency of test 13 was higher than that of test 10 resulted from an excessive air supply instead of the method of firing is obvious on examining the results of test 15, fired by the coking

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method, with 118 per cent excess air in the flue gases, and test 9, fired by the spreading method with 101 per cent excess air in the flue gases, at practically the same rates of steaming.

In these tests there was far less difference in the excess air present, and in the flue-gas temperatures, while the efficiencies differed by only 0.7 per cent.

On examining the results of the tests with bituminous coal it became clear that what seemed the best gas analysis obtainable—that is, carbon dioxide as high as possible with little or no carbon monoxide—was not shown by the tests to be the best, for the thermal efficiency was higher with higher excess air. It was decided therefore to run a test (16) at a high rating, firing by the spreading method and using about 100 per cent excess air, to compare the results of this test with the previous test (11), at the high rating with about 40 per cent excess air. In spite of test 16 being run at about 10 per cent higher rating than test 11, with about 50 per cent more air per pound of coal, the flue-gas temperature was 170° F. lower, so that the loss due to the dry flue gas was only slightly higher. The efficiency (68.5) during test 16, with the increased air supply, was the highest obtained with bituminous coal, and was 3.7 per cent higher than in test 11 (at the higher rating); this increase in efficiency is, however, to be attributed only in part to the excess air burning the gases more rapidly, for the loss through unburned combustible in the ash was higher in test 11. If the heat lost in the combustible in the ash be deducted from the available heat, then the efficiencies based on fuel gasified, or combustible consumed, are 69.8 with the larger air supply (test 16), and 68 per cent with the smaller air supply. It will be observed (item 51, Table 1) that the undetermined losses are less in test 16 than in test 11, which may be attributed partly to less loss in unburned tars and soot.

There is a big contrast between the effect of admitting extra air to burn coke and to burn bituminous coal. Test 14A was made with 129 per cent excess air and at a slightly lower rate of steaming than test 14, but the flue-gas temperature with the larger air supply was 65° F. higher, and the efficiency about 7 per cent less.

Test 17, with bituminous coal, was run at approximately the same rating as test 12, but with a smaller grate, to see if the boiler could be operated with bituminous coal at a low rating with less excess air than in test 12, by increasing the combustion rate per square foot of grate. As the results show, however, the excess air was about the same in both tests, and the efficiency in test 17 with the smaller grate was slightly lower.

The line (Fig. 6, p. 17) showing the boiler efficiency when burning the coarser coke breeze lies slightly below the bituminous coal line, because the ash and refuse losses were greater when burning it at the same rating.

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In Figure 6 the efficiency line for the finer coke-breeze mixture starts on the left from a point slightly below the line showing the efficiency with the coarse coke-breeze mixture; but at a rate of steaming about 30 per cent higher, the efficiency is seen to be about 4 per cent lower, because of an increase of excess air in the flue gases.

HEAT CARRIED AWAY BY STEAM IN FLUE GAS.

Item 40 in Table 1 shows the heat carried away by the steam in the flue gas to be higher for bituminous coal than for anthracite, and higher for the latter than for coke, and that these differences are due almost entirely to differences in the hydrogen content of the fuels. The quantity of steam in the flue gas per pound of fuel fired, if the hydrogen in the fuel is all burned, is equal to 9 times the hydrogen content of 1 pound of fuel; the total heat of 1 pound of steam at very low pressure, and at the temperature of the flue gas, above 1 pound of water at air temperature, may be expressed by $0.47\ T+1086-t$, where T is the temperature of the flue gas and t the temperature of the air. The total heat carried away per pound of fuel fired is therefore equal to $9\ H\ (0.47\ T+1086-t)$, where H is the pounds of hydrogen per pound of fuel fired. It is impracticable to recover the whole of this total heat of steam, as when Pittsburgh coal burns completely in air saturated with water vapor, at 60° F., so that no oxygen is present after burning, the gas formed has the following composition by volume:

Composition of gases of combustion from Pittsburgh coal burning in moisture-saturated air.

	Per cent.
Carbon dioxide	16.8
Sulphur dioxide	0.1
Steam	8.6
Nitrogen	74.5
Total	100.0

Of the total steam in this gas, 6.9 volumes come from the coal and the remaining 1.7 volumes from the air, and if the gases were cooled at constant pressure the steam would only begin to condense at 110° F., and all the steam from the coal would be completely condensed at about the dew point of the air, 60° F.

It is not impossible to construct an air or feed-water economizer that will reduce the temperature of the gases and condense most of the steam without corroding the heating surface with water containing dissolved sulphur dioxide; but it is impracticable, and in waste-heat economizers care is taken not to lower the temperature of the gases below the dew point.

The calorific value ordinarily used in steaming tests is determined by burning the fuel in compressed oxygen in a bomb calorimeter, and

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includes the heat given up by the products of combustion in returning to the initial temperature and by the condensation of the steam formed from the fuel.

To allow for the impracticability of condensing the steam in the flue gas from a boiler, the thermal efficiency of the boiler is sometimes taken as the ratio of the heat used for steam raising to the net calorific value of the fuel, which is calculated from the commonly used gross calorific value by making an allowance for the heat liberated in condensing the steam in the calorimeter. Values ranging from 1,080 to 1,040 B. t. u. are used for the latent heat of the steam. In this paper the latent heat is taken as 1,040 B. t. u. per pound, which is the value suggested by the American Society for Testing Materials, and to obtain the net calorific value of the fuel, 1,040 B. t. u. must be deducted from the gross calorific value for each pound of steam formed per pound of fuel, or $9 \times H \times 1{,}040$ B. t. u., must be deducted from the gross calorific value of the fuel.

The following table shows the efficiencies of the boiler when based on the net calorific value for some representative tests:

TABLE 2.—*Comparison of thermal efficiencies based on the gross and net calorific values of the fuels.*

Fuel.	Thermal efficiencies based on gross calorific values.					Thermal efficiencies based on net calorific values.				
	Coke.	Anthracite.	Bituminous.	Bituminous and coke breeze.		Coke.	Anthracite.	Bituminous.	Bituminous and coke breeze.	
				Coarse.	Fine.				Coarse.	Fine.
Thermal efficiency, per cent	79.0	77.3	66.6	62.3	61.5	79.6	79.0	69.2	64.0	63.1
Per cent of builder's rating	26	28	36	31	34	26	28	36	31	34
Thermal efficiency, per cent	76.6	74.0	64.6	.....	57.3	77.2	75.6	67.0	.....	58.9
Per cent of builder's rating	50	54	56	.....	45	50	54	56	.....	45
Thermal efficiency, per cent	73.8	65.8	64.9	64.8	.....	74.4	67.4	67.3	66.5	.....
Per cent of builder's rating	80	89	85	71	.....	80	89	85	71	.....
Thermal efficiency, per cent	73.5	65.8	68.5	.....	.....	74.1	67.3	71.2	.....	.....
Per cent of builder's rating	113	102	117	.....	.....	113	102	117	.....	.....

Table 2 shows that the increase in efficiency of the bituminous coal tests, based on the net calorific value, is about 4 per cent of the efficiency based on the gross calorific value, whereas it is less than 1 per cent for the coke tests and anthracite tests.

LOSS THROUGH COMBUSTIBLE IN ASH.

The loss of combustible matter in ashes depends upon the ash content of the fuel, and the combustible content of the ash and refuse removed from the ash pit and grate. The latter depends on the size

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of the air openings in the grates, size of the fuel, design of the grates, manipulation of the fire, fusibility, and other physical properties of the ash.

The bituminous coal contained 6 to 11 per cent ash, the anthracite 10 to 16.5 per cent, the coke breeze and bituminous coal mixtures about 17 per cent, and the coke 15 to 21.5 per cent. The heat loss (item 50 in Table 1) is 2 to 5 per cent of the heat in the bituminous coal, 4 to 7 per cent of the heat in the coke, and 7 to 12 per cent of the heat in the anthracite. Thus, although the anthracite contained less ash than the coke, yet more combustible accompanied the anthracite ash. These three fuels were burned both on fixed grate bars with the smaller air spaces ($\frac{1}{4}$ inch), and on shaking grate bars with the larger air spaces ($\frac{1}{2}$ inch), but there was no conclusive evidence to show that the loss of combustible in the ash was less through the fixed bars than in that through the shaking bars. But in burning the coarser grade coke breeze and bituminous coal mixture on fixed bars, the heat loss from combustible in the ash and refuse was about half the heat loss in burning the mixture on shaking grate bars, as is shown by the following table:

TABLE 3.—*Combustible loss with shaking and fixed grate bars.*

Test number.	1 SA.	2 SA.
Grate	Shaking.	Fixed.
Air space in bars, inches	0.5	0.25
Air space, per cent total grate area	52	31
Fuel fired per hour, pounds	168	368
Combustible in ash and refuse, per cent	31.9	20.1
Heat loss per pound of fuel by not burning this combustible, B. t. u.	1,058	555
Heat loss, per cent heat in fuel	9.4	4.9

The fixed bars were used during both tests with the mixture of bituminous coal and the finer coke breeze and the combustible in the ash contained a considerably higher proportion of the heat in the fuel than when the mixture of bituminous coal and coarse coke breeze was burned.

HEAT CARRIED AWAY BY DRY FLUE GASES.

The heat losses caused by the dry flue gases leaving at a high temperature are shown in Figure 7 (p. 18) for the various fuels. For anthracite these losses were a little higher at the higher rates of steaming than for coke, with one exception (test 14A, with coke), and were lower than the losses for bituminous coal alone or mixed with coke breeze. The abnormally high dry flue-gas loss with coke during test 14A was due to the high excess air, which not only caused a direct loss by increasing the mass of the flue gases per pound of fuel, but also raised the loss because the larger mass of gases was cooled less

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in passing through the boiler and left at a higher temperature. Similarly the point shown above the anthracite line is due to excess air.

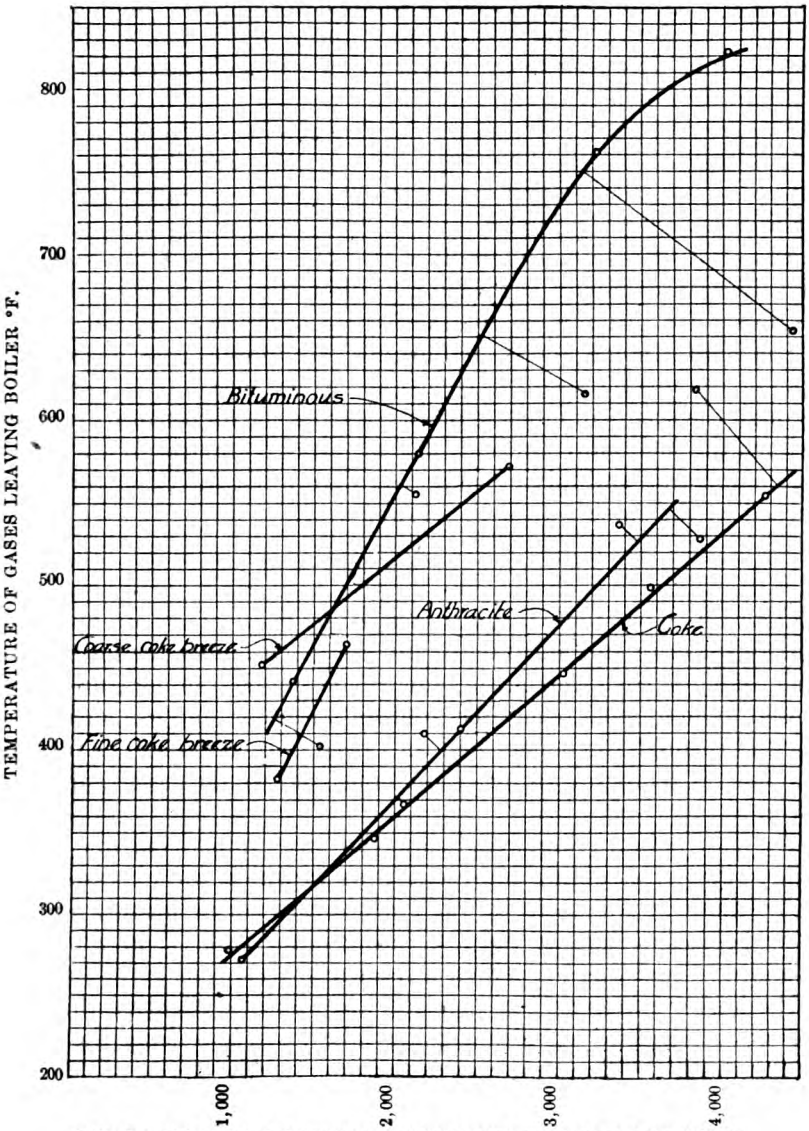

FIG. 9.—Flue-gas temperatures at different rates of steaming.

In Figure 7 the dry flue-gas losses with bituminous coal, for all tests except three, lie nearly on a straight line. Of the two tests well above the line, the one shown to the left was for test 15, when coal was fired by the coking method, and both the flue-gas temperature and excess air were high; and the one to the right was for test 16, run at

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a high rating, when additional air was admitted over the fuel-bed in order to ascertain the effect on the efficiency. The point shown well below the bituminous coal line to the left corresponds to test 17, in which the coal was burned on a smaller grate. The flue-gas losses were lower during this test because the flue-gas temperature was lower, probably owing to the longer mean travel of the gases from the grate to the stack.

The line representing the normal flue-gas losses from bituminous coal is well above the lines representing the normal flue-gas losses with coke and anthracite, because the flue-gas temperature and excess air was considerably higher; as the rate of steaming increased, the excess air decreased considerably with bituminous coal, but increased slightly with coke and anthracite, so that the difference in the flue-gas losses for bituminous coal and these other two fuels decreased.

The high flue-gas losses in burning bituminous coal mixed with coke breeze are the result of excess air, which may have come partly through the fuel bed, but was probably from the higher draft required to burn the fuel, more air being drawn through crevices in the base of the combustion and mixing chambers than when the other fuels were burned at the same rate with a lower draft.

FLUE-GAS TEMPERATURE.

Figure 9 shows temperatures of the flue gas. They do not differ greatly for coke and anthracite, but are much higher for bituminous coal than for coke and anthracite. The higher temperatures were caused by more heat being liberated by tars, soot, and gas burning on the way through the boiler; had they been burned nearer the furnace, the flue-gas temperature for bituminous coal would have been much lower.

The two points lying well below the bituminous coal line at the higher rates of steaming represent tests in which the excess air was higher than in the tests through which the curve passes, and the point below the line at the low rating is for test 17, in which the bituminous coal was burned on a smaller grate.

The higher excess air had precisely the opposite effect on the point well above the line representing the coke tests, as raising the excess air increased the flue-gas temperature.

EXCESS AIR IN THE FLUE GASES.

Figure 10 shows the excess air in the flue gases when the several fuels were burned at different rates. In burning anthracite and coke the mean excess air is shown to increase slightly with the load, and to decrease considerably with bituminous coal. The point showing the

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abnormally high excess air content at the highest rating with bituminous coal was for test 16, in which more air was deliberately admitted to the furnace. It was impossible to burn the bituminous coal at low rates of steaming with as small an excess air content as with coke or anthracite, without having a high carbon monoxide content in the flue gas. At high rates of steaming, bituminous coal could be burned with less excess air than could either anthracite or coke. Evidently, at high rates of steaming, the flow of gases at the higher velocity

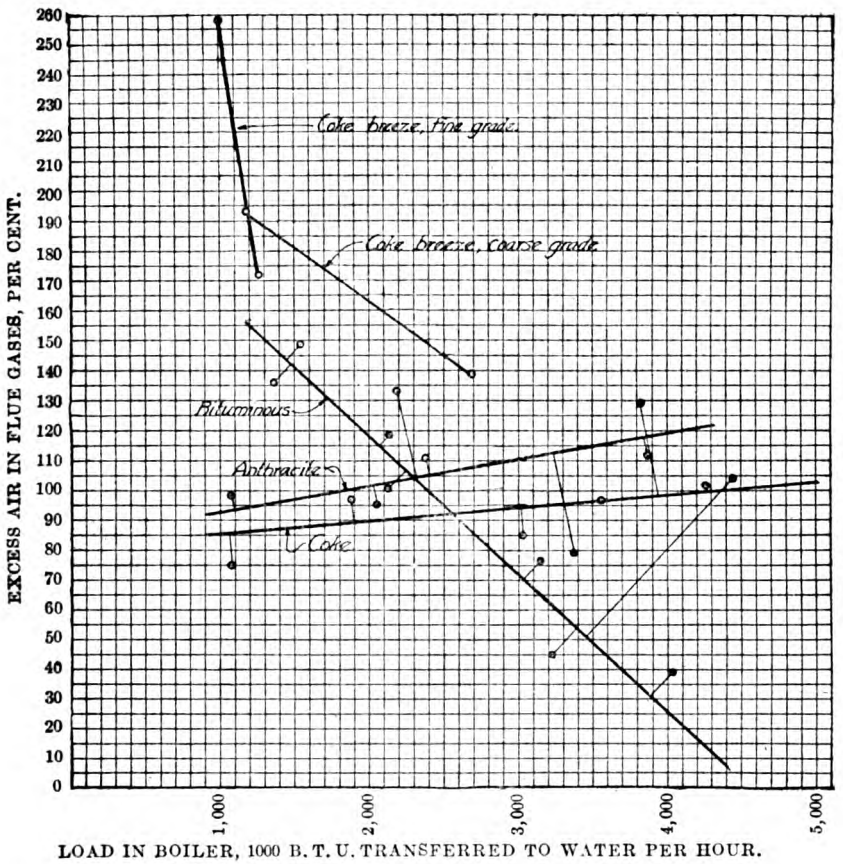

FIG. 10.—Excess air in flue gases at different rates of steaming with the several fuels.

was more turbulent, which caused the air admitted over the fire to mix more thoroughly with the gases rising from the fuel bed, and this made it possible to burn the gases from the bituminous coal fire with less air at high than at low rates of steaming. Probably the higher excess air with anthracite or coke at high ratings is due partly to channels through which the air passes, forming in the fuel bed, and to leakage of air into the flues under the higher draft required at the higher rating.

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EXCESS AIR, TEMPERATURE, AND FLUE-GAS LOSS.

When the air supply above the fuel bed of a boiler is increased, and the rate of steaming is kept constant, the loss due to the sensible heat in the flue gases usually increases because of the increased mass and temperature of the gases, and the admission of an extra supply of air is justified only if it reduces the combustible contents of the flue gases enough to offset the loss as sensible heat.

This effect of the increase in the air supply is shown in tests 14 and 14A, run roughly at the same rating. During test 14 there was 102 per cent excess air, the flue-gas temperature was 554° F., and the dry flue-gas loss was 17.9 per cent; but on increasing the excess air in test 14A to 129 per cent, the temperature rose to 619° F. and the loss to 23.8 per cent; yet a comparison of two other tests with bituminous coal shows that the admission of more air over the fire bed actually reduced the loss due to sensible heat in the flue gases.

These bituminous coal tests were No. 10 with 45 per cent and No. 13 with 77 per cent excess air, at practically the same rating. The flue-gas temperature (616° F.), with the greater excess air was so much lower than with the smaller excess air (761° F.), that in spite of the larger quantity of flue gas the loss due to sensible heat in the flue gas was slightly lower during No. 13, and the greater air supply burned the combustible gases more thoroughly, so that the thermal efficiency was raised. But in a further short test at the same rating with a still greater air supply, although the gas temperature decreased the loss through sensible heat in the flue gas increased again.

The effect of the air supply on the observed flue-gas losses for these three tests is shown in Table 4.

TABLE 4.—*Effect of excess air on flue-gas losses.*

Item.	Test 10.	Test 15.	Test E.
Per cent of maker's rating	85	83	87
Carbon dioxide, per cent	11.9	9.2	7.9
Carbon monoxide, per cent	0.4	0.1	0.1
Excess air, per cent	45	77	121
Flue-gas temperature, °F	761	616	570
Flue-gas losses:			
Loss through steam in flue gas, per cent	4.7	4.5	4.6
Loss in dry flue gas, per cent	18.3	18.1	20.3
Loss through carbon monoxide, per cent	1.7	0.3	0.7
Total flue-gas losses, per cent	24.7	22.9	25.6

Another example of a considerable reduction of flue-gas temperature with an increase in the excess air is shown by comparing the results of test 16 (104 per cent excess air and a flue-gas temperature of only 654° F.) with those of test 11 at a lower rating (only 39 per cent excess air and a temperature of 822° F.). The dry flue-gas and carbon monoxide losses were greater in test 16 but the efficiency was

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nearly 4 per cent greater, which may be attributed partly to the excess air reducing the tar, soot, and radiation losses and partly to the lower losses in ash and refuse.

The upper part of Figure 11 shows how the temperature of the flue gas changed as the air supply was increased while the rate of steaming

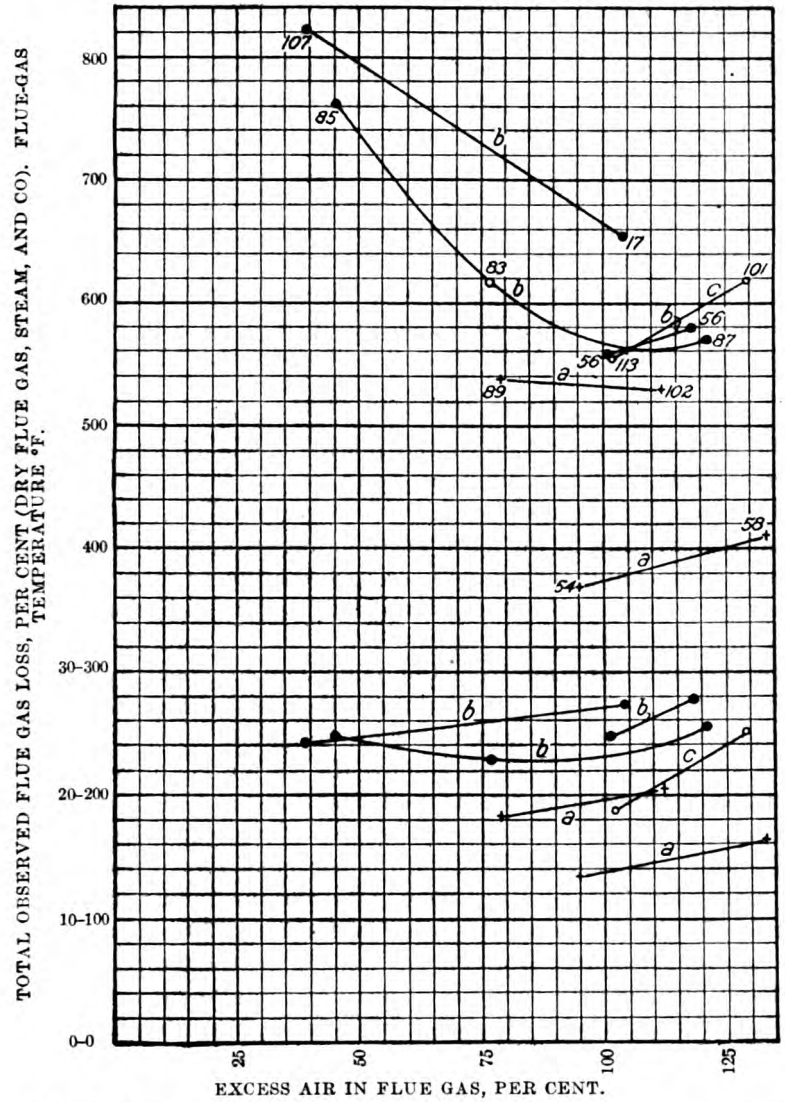

Fig. 11.—Variation, at approximately constant steaming rates, of the gas temperature and total sensible and chemical energy in the flue gas as the air supply varies: *a*, Anthracite; *b*, bituminous; *c*, coke. Numbers represent per cent of maker's rating.

was kept approximately constant for several tests. It will be observed that, for three tests at about 85 per cent rating, as the excess air increased from a small value, the flue-gas temperature dropped rapidly at first, and then more slowly until a little over 100 per cent

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excess air was present in the flue gases, when on further increasing the excess air the flue-gas temperature rose. This marked drop in temperature under this condition was observed only when burning bituminous coal, although a slight drop was noticed when burning anthracite and increasing the excess air from 79 to 112 per cent.

The lower part of Figure 11 shows the variation of the total observed flue-gas losses with the excess air. For the three tests at about 85 per cent rating, the observed total flue-gas losses reached a minimum with about 80 per cent excess air; had the tar and soot losses been determined and added to that total, the minimum losses would probably have occurred with a still greater content of excess air.

In view of the high efficiency in test 16 with the high excess air, and the marked drop in temperature as the excess air increases up to about 100 per cent, it is probable that this boiler is most efficient when burning bituminous coal, with 80 to 100 per cent excess air in the flue gases. Obviously, more draft will be required to force this additional air through the boiler at the higher ratings.

TEMPERATURE IN FURNACE.

The temperatures of an exposed platinum and platinum-rhodium thermocouple placed in different parts of the furnace were measured in some of the tests. This thermocouple did not indicate the actual temperature of the gases surrounding it, and the temperature of the thermocouple may have been higher or lower than that of the surrounding gases. If lower, it received heat by radiation from the flame and imparted it to the gases, and if higher, it received heat by convection and radiation from the flame, and lost heat by radiation to the walls. But since the thermocouple was small, it gave a fairly accurate indication of the temperature in the furnace.

The two curves in Figure 12 show the variations of temperature when the thermocouple was moved over the fire-bed from front to back, and across the mixing chamber, on a level with the top of the bridge wall, and midway between the center of the furnace and the side wall. One temperature curve was obtained while burning 370 pounds of coke per hour, the other in burning 370 pounds of bituminous coal per hour. Both curves are similar; the temperature near the front was comparatively low, because the gases rising from the fuel-bed were diluted with air entering through the fire doors; then toward the center of the furnace, the temperature rose rapidly, showing that more heat was generated by burning the gases than was given up to the furnace walls by the flame. As the gases approached the bridge wall they burned slower, because most of the oxygen in the air entering through the fire doors had already combined with the combustible gases, and the heat generated was less than the heat lost, so that the temperature fell. On crossing the bridge wall, the tempera-

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ture rose on account of a further supply of air, which leaked in through crevices in the mixing chamber, meeting the gas current and oxidizing further its combustible contents.

These temperature curves represent the temperature along only one horizontal line through the furnace and mixing chamber.

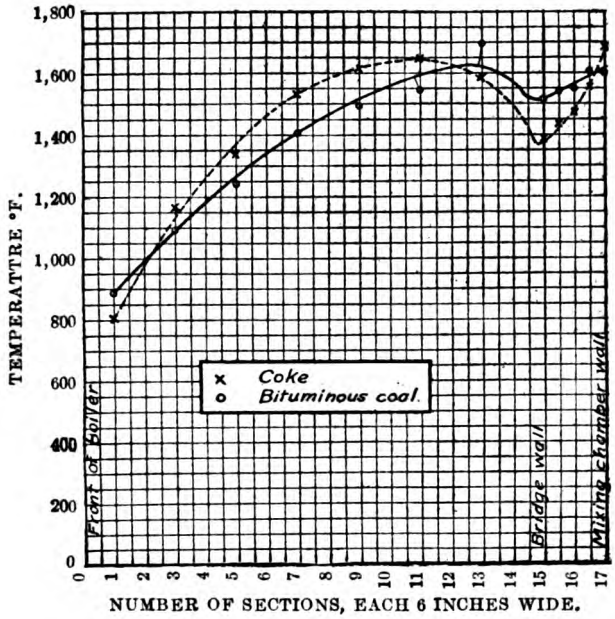

Fig. 12.—Temperatures over fuel bed and in mixing chamber.

Other measurements during tests 8A and 4SA showed how the temperatures varied in transverse vertical planes across the furnace. These were measured in vertical planes, one coplanar with the opening through the bridge-wall and the other across the furnace midway between the furnace front and bridge sections. The following tabulations show the mean of several of these temperatures:

TABLE 5.—*Temperatures, °F., in plane of right-hand opening over bridge-wall.*

Test 8A, anthracite; 102 per cent rating.

	Nearest center of furnace.	Center of opening.	Nearest furnace wall.
Top of opening	1,805	1,740	1,610
Center of opening	1,730	1,650	1,760
Bottom of opening	1,790	1,720	1,650

Test 4SA, fine coke breeze and bituminous coal; 34 per cent rating.

	Nearest center of furnace.	Center of opening.	Nearest furnace wall.
Top of opening	1,080	1,020	1,040
Bottom of opening	960	940	990

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The above shows that in test 8A the temperature was highest at the side of the opening towards the center of the furnace, where the velocity of the gas was highest, and lowest in the top right-hand corner; but the temperature at this corner was only 40° F. lower than the temperature at the center, and the variation of the temperature is so inconsistent that no definite conclusions may be drawn.

In test 4SA, the temperatures at the top of the opening were higher than those at the bottom, and the highest temperature shown was 140° F. higher than the lowest.

TABLE 6.—*Furnace temperatures, °F., in vertical plane midway between bridge-wall and front of furnace, between center line and right-hand wall.*

Test 8A, anthracite; 102 per cent rating.

	Center line furnace.	Center line of right fire door.	Near right wall.
Near roof of furnace	1,700	1,555	1,570
Twelve inches above fire-bed	1,745	1,675	1,760
Just above fire-bed	1,795	1,775	1,790

Test 4SA, fine coke breeze and bituminous coal; 34 per cent rating.

	Center line of furnace.	Center line of right fire door.
Near roof of furnace	1,245	1,230
Twelve inches above fire-bed	1,230	1,233
Just above fire-bed	1,230	1,245

The furnace temperatures shown in Table 6, and observed during test 8A, were highest near the fuel bed; but when the thermocouple was near the fuel bed, a much smaller area was exposed to the radiation of the furnace walls, and a larger area exposed to radiation from the fuel bed, so that the higher temperature was partly due to smaller loss through radiation to the walls and greater gain by radiation from the fuel bed. The furnace temperatures measured during test 8A differed little from these observed when the gases left the furnace, which showed that from this section to the opening, the combustible gases had burned and given off enough heat to compensate for the heat the gases lost to the furnace walls on their way to the bridge wall.

The furnace temperatures during test 4SA (coke breeze mixed with bituminous coal) are seen from the table to differ little in different parts of the furnace. They were lower than the corresponding temperatures in test 8A (anthracite), because the excess air supply was greater, the rate of combustion was lower, and a larger proportion of the heat generated by combustion in and above the fuel-bed

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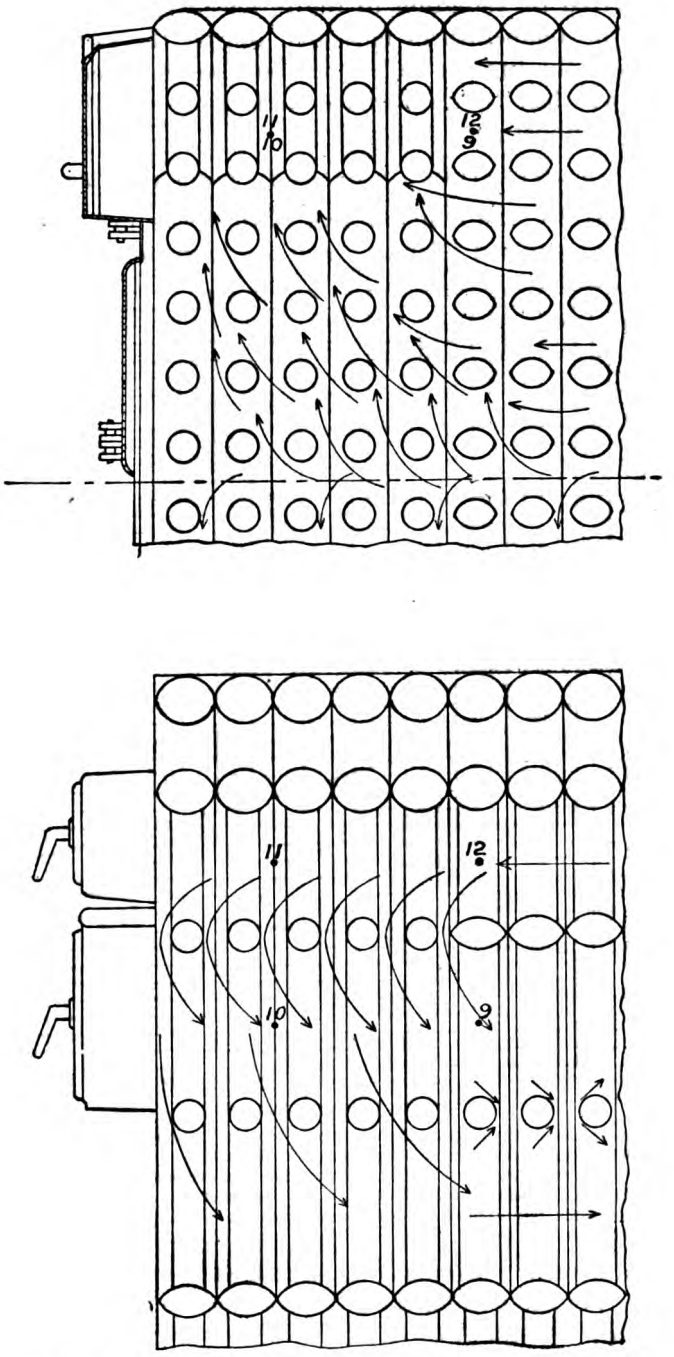

FIG. 13.—Position of thermocouples 9, 10, 11, and 12, used to measure the temperature of the gases flowing from the upper to the lower pass.

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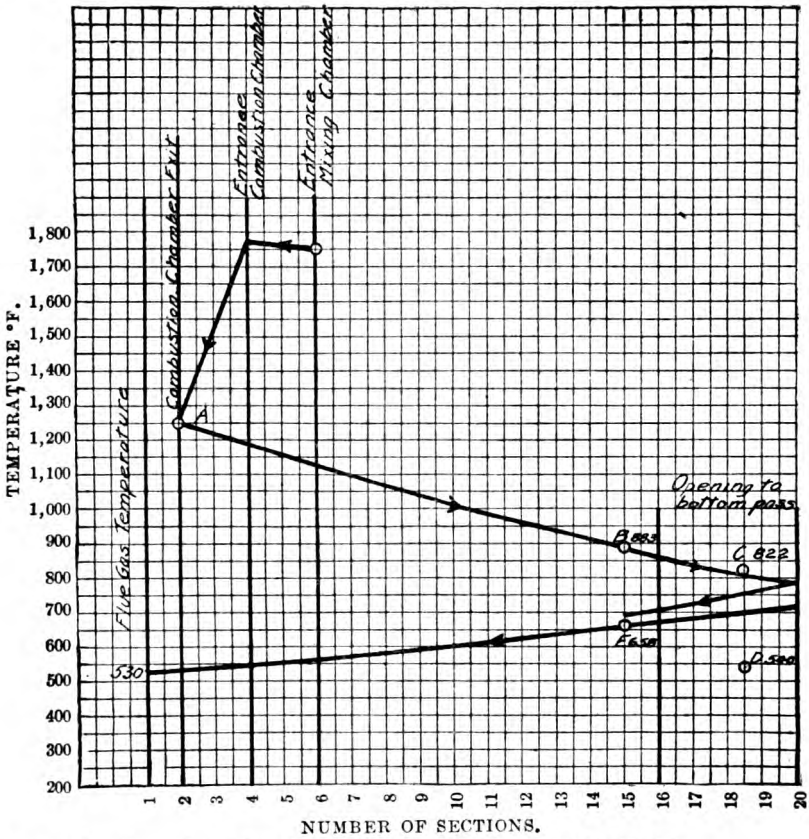
was transferred by radiation to the furnace walls. They are higher also than the temperatures measured during the same test in the opening from the furnace to the combustion chamber, which shows that heat was lost to the furnace walls more rapidly than it was gained by combustion.

TEMPERATURE OF GASES IN BOILER FLUES.

During test 8A, the temperatures of the gases in and leaving the furnace were measured (Tables 5 and 6). Continuously throughout



A, mean of continous observation of three thermocouples, top combustion chamber.
B and *C*, mean of continuous observation of temperature in top pass.
D and *E*, mean of continuous observation of temperature in upper inside section, bottom pass.
FIG. 14.—General trend of the temperature of the gases across each section of the boiler: Mean of continuous observation of temperatures in *A*, top combustion chamber; *B* and *C*, top pass; *D* and *E*, upper inside section of bottom pass.

the test, temperatures were also measured at the top of the combustion chamber, in the path of the gases leaving the top pass and entering the lower pass, and at the exit of the gases from the boiler.

The temperature of the gases leaving the combustion chamber was measured at the three points *m*, *n*, *p*, shown in Figure 4 (p. 9), and was as follows: Left center, *m*, 1,310° F.; right center, *n*, 1,284° F.;

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right side, *p*, 1,180° F. These figures show that the gases were hottest at the center because they entered the combustion chamber at the center and traveled a shorter distance to the center of the exit than to its sides.

Points 9, 10, 11, and 12, in Figure 13, show where the temperatures of the gases were measured in their passage from the top to the bottom pass; the readings were as follows:

Temperatures, °F., of gases at four points.

	Point 11.	Point 12.
Top pass	822	883
	Point 10.	Point 9.
Bottom pass	540	658

Figure 14 shows the general trend of the temperature of the gases across each section, where the observed temperatures from the combustion chamber to the stack are joined by curves, on the assumption that the rate of fall per section passed over is proportional to $(t - 230)$, where t is the temperature of the gas and 230 is about 3° F. above the temperature in the boiler. The mean rate of temperature drop per section in the top pass is $0.034 \times (t - 230)$, and in the return along the bottom pass is $0.025 \times (t - 230)$. Both curves are continued to the front end of the boiler.

It will be noticed that the upper temperature curve continued into the region where the gases turn downward is only slightly below the observed temperature (822° F.); and that the curve, on being continued back from the front, is only about 30° F. above the gas temperature (658° F.) noted at point 9 in Figure 13. But the low temperature observed at point 10 (540° F.) shows that the main gas stream does not sweep out the space round point 10, but keeps close to the horizontal barrier when dipping downwards. The drop in temperature between points 12 and 9 immediately below, but separated by the barrier, is decidedly high, and shows how turbulent in turning the gas flow must be to enable it to give up so much heat.

Figure 15 shows temperature curves obtained by moving the thermocouples from section to section through the boiler. *A A* represents the temperature in the top pass between the top of the combustion chamber and the front of the boiler, along a horizontal line in the second clear opening from the left. The curve does not show a constant drop of temperature per section per mean temperature difference in degrees, because the temperatures were not read in a stream of constant mass flow; but in a stream moving slowly at first, and then gradually gaining velocity as it is joined by gases from the center of the top pass, moving to the side toward the front rectangular opening and flowing down to the lower pass. The curve *A A* therefore falls more rapidly per degree of temperature difference in its higher part, because here the gases move more slowly than later when approaching the opening to the bottom pass.

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Over the opening the curve *A A* falls rapidly. The curve *B B* represents the temperature in the same vertical plane as *A A*, but in the upper section of the bottom pass; *C C* was taken in the section below *B B*. These curves show the gases to be comparatively cool near the front, and to become hotter as they move toward the back. The gases near the front are moving very slowly, and are well out of the main stream of gases, which, as the temperature curves show, keeps close to the barrier in flowing to the bottom pass from the top pass.

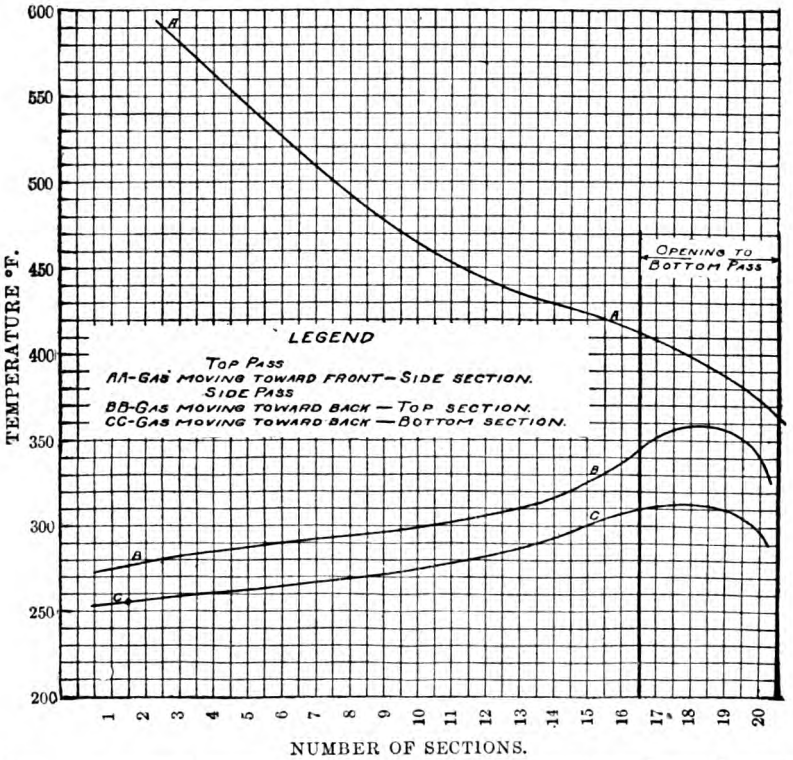

FIG. 15.—Curves showing temperature of gases along path from the top of the combustion chamber to the breeching.

These curves also show how the very turbulent flow in rounding the horizontal barrier helps the gases to come into contact with the cooler walls and give up heat. This greater turbulence continues for some distance along the lower pass, as is shown by the rate of drop of the temperature, being higher in the earlier part of the curves *B B* and *C C* than in the part nearer the back. This rate of temperature drop near the front of the bottom pass is much larger than could be accounted for by the higher temperature near the front.

The gases move in each of the bottom passes through four main openings through the sections. During test 5, with anthracite, the

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mean temperatures (°F.) of the gases leaving the centers of these sections were as follows:

Mean temperatures, °F., of gases leaving sections.

	Outside.	Inside.	Difference.
Top	370	385	15
Bottom	350	358	8
Difference	20	27	.....

CONNECTION BETWEEN TEMPERATURE DROP AND GAS FLOW.

Table 7 shows the temperatures of the gases leaving the combustion chamber and leaving the boiler. The tests are arranged so that tests with a large rate of gas flow succeed those with a smaller rate. In the fuel column the letter B signifies bituminous coal; M_f, fine coke breeze and coal mixture; M_c, coarse coke breeze and coal; A, anthracite; and C, coke.

TABLE 7.—*Temperature drop and gas flow.*

Test.	Fuel.	Rate of steaming, 1,000 B. t. u. per hour.	Flue gas per hour (pounds).	Excess air (per cent).	Temperature leaving combustion chamber, °F.					Flue gas temperature, °F.	Drop in temperature, center to flue, °F.	Drop in temperature per mean degree difference, °F.
					Side.	Near center.	Near center.	Side.	Mean center temperature, °F.			
1	2	3	4	5	6	7	8	9	10	11	12	13
12	B	1,370	3,970	136	758	788	817	764	803	441	362	1.0
SA4	M_f	1,272	3,974	172	.....	783	813	.....	798	382	416	1.3
SA1	M_c	1,184	4,289	193	705	.....	780	.....	780	452	328	0.9
17	B	1,540	4,426	148	653	704	710	648	707	402	305	1.0
15	B	2,133	5,594	118	956	1,039	1,055	993	1,047	580	467	0.8
7	A	2,397	5,638	133	975	1,036	.....	.....	1,036	410	626	1.5
8	A	3,377	7,130	79	.....	1,427	1,507	.....	1,467	537	930	1.4
E [1]	B	3,290	7,830	121	922	1,028	1,039	950	1,033	570	463	0.9
SA2	M_c	2,694	7,982	138	.....	.....	963	.....	963	571	392	0.8
SA3	M_f	1,700	8,013	258	.....	.....	669	.....	669	464	205	0.6
14	C	4,270	9,100	102	.....	.....	1,284	.....	1,284	554	730	1.2
8A	A	3,865	9,560	112	.....	1,310	1,284	1,180	1,297	529	768	1.3
16	B	4,430	10,437	104	1,036	.....	1,122	1,039	1,122	654	468	0.7
14A	C	3,827	10,870	129	978	1,055	1,042	870	1,048	619	429	0.7

[1] This test was run for 6 hours only, and is not mentioned in the table showing the principal results.

The figures in the last column of Table 7 are calculated from the mean temperature of the gases at the center of the top of the combustion chamber, the flue-gas temperature at the exit, and the temperature of the steam, by assuming that for a constant gas flow the drop in temperature per unit area of heating surface passed over by the gases is proportional to the difference between the temperature of the gas for this area and the temperature of the steam. This

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assumption is based on experimental evidence, which shows that no great error is involved in using it, provided the gases do not burn in their passage between the two points and the flow is continuous. On this assumption, where T is the gas temperature, t the steam temperature, S the heating surface, and C a constant expressing the drop in temperature per degree temperature difference per unit area of heating surface, the fall of gas temperature along the path of gas flow may be expressed by

$$-\frac{dT}{dS}=C(T-t)$$

and on integrating between the limits T_1 and T_2,

$$\text{Log}_e\left(\frac{T_1-t}{T_2-t}\right)=C\,S$$

where T_1 is the initial and T_2 the final temperature, and S the total heating surface cooling the gases from T_1 to T_2.

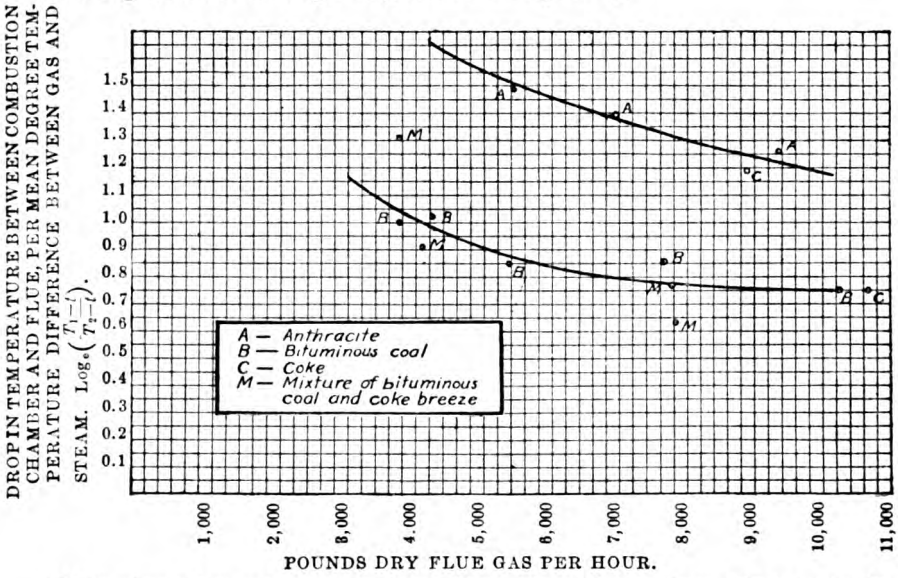

FIG. 16.—Drop in temperature per mean degree of temperature difference of gases between combustion chamber and exit from boiler.

$\text{Log}_e\dfrac{T_1-t}{T_2-t}=C\,S$, therefore represents the drop in temperature per mean degree temperature difference for the whole surface passed over.

Experiments have shown that the higher the rate of gas flow at a constant temperature over a small portion of the heating surface the less the drop in temperature at that place, and that approximately for the whole heating surface

$$\text{Log}_e\frac{T_1-t}{T_2-t}=\frac{a}{w}+b$$

where a and b are constants and w the mass of gas flowing per hour.

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If the above equation holds for a boiler, then points representing $\text{Log}_e \frac{T_1 - t}{T_2 - t}$ for each test plotted on w should lie on a single curve. These points have been plotted in Figure 16; but the points lie in two distinct curves, the upper containing no tests with bituminous coal, and the lower with the exception of test 14A, with coke, solely represents tests with bituminous coal. It is obvious, therefore, that the temperature of the gas from the bituminous coal fires fell less than that of the gas from the anthracite or coke fires for the same rate of gas flow. This smaller drop in temperature with bituminous coal may be attributed either to a source of heat resulting from the combustion of gases and soot between the combustion chamber and flue-gas exit, or to the deposition of soot on the heating surface. Had it been caused by the deposition of soot, then the flue-gas temperatures would have been much lower at the beginning than at the end of a test; but an examination of the complete records showed that these temperatures did not rise materially as the test progressed. The smaller temperature drop through the boiler, when burning bituminous coal, was due therefore to the combustion of gases, tars, and soot, which continued after the gases had left the combustion chamber.

COMBUSTIBLE GASES, TAR, AND SOOT LEAVING FURNACE AND COMBUSTION CHAMBER.

To determine the combustible constituents of the gas leaving the furnace and combustion chamber, when burning bituminous coal, samples were drawn off through a water-cooled tube and analyzed. Their analyses are shown in Table 8.

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TABLE 8.—*Gas and tar samples from Pittsburgh lump coal (grate-back half bridged off).*

Test.	Rate.	Time.	Position.	Gas analysis, per cent by volume.							Tar, grams per cubic foot.	Soot, grams per cubic foot.	Mean distance from fuel-bed (feet).	Flue gas.			
				CO_2.	C_2H_4.	O_2.	CO.	CH_4.	H_2.	N_2.				CO_2.	O_2.	CO.	Temperature, °F.
17 special...	Low.....	Before firing	Bridge wall	18.7	0.0	0.5	1.7	0.0	0.0	79.1	0.005	0.016	5	9.6	10.8	0.0	367
			Top pass	15.8	.0	4.0	.9	.0	.0	79.3	.002	.027	10	.....	.....	.....	.....
		After firing	Bridge wall	8.8	.0	8.2	2.4	.8	.6	79.2	.079	.178	5	7.0	11.0	1.4	384
			Top pass	8.1	.0	8.7	2.4	.3	.7	79.8	.070	.199	10	.....	.....	.....	.....
	Medium....	Before firing	Bridge wall	.....	.....	.....	.....	.....	.....	.....	.....	.....	5	[1] 4.8	[1] 16.2	[1] .0	[1] 310
			Top pass	.....	.....	.....	.....	.....	.....	.....	.....	.....	10	([1])	([1])	([1])	([1])
		After firing	Bridge wall	12.7	.0	4.3	.9	.1	.3	81.7	.026	.217	5	6.2	13.0	.0	410
			Top pass	11.0	.0	6.0	1.1	.3	.4	81.2	.034	.362	10	.....	.....	.....	.....
	High.....	Before firing	Bridge wall	15.8	.0	4.6	.0	.0	.0	79.6	.011	.050	5	9.0	11.4	.0	655
			Top pass	13.1	.0	6.8	.0	.0	.0	80.1	Lost.	.043	10	.....	.....	.....	.....
		After firing	Bridge wall	.....	.....	.....	.....	.....	.....	.....	.....	.....	5	10.4	8.4	.0	695
			Top pass	.....	.....	.....	.....	.....	.....	.....	.025	.211	10	.....	.....	.....	.....

[1] No tar or soot, as filter tube was not discolored.

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The figures in the three following tables have been calculated from the foregoing table and show the heat energy present in the gas as combustible, expressed as a percentage of the heat energy in the coal fired:

Low rating, heat in combustible in gas, percentage of heat in coal.

	Before firing.			After firing.		
	Bridge wall.	Top combustion chamber.	Flue gas.	Bridge wall.	Top combustion chamber.	Flue gas.
Tar	0.2	0.1	.....	4	4	.....
Soot	0.4	0.9	.....	8	10	.....
Gas	4.7	3.0	.....	26	20	0.9
Total	5.3	4.0	.....	38	34	0.9

This table shows that far less combustible was present in the gas before than after firing, at which times more soot was present in the gas after leaving the combustion chamber than on entering it, probably in part at least because of the carbonization of the tar and dissociation of the methane ($CH_4 = C + 2\ H_2$). This dissociation may also account for the hydrogen content of the gas leaving the combustion chamber being greater than that of the entering gas. At the medium rating, neither soot nor tar was found in samples of gas taken just before firing. After firing at the medium rating, the heat energy in the gas was as follows:

Medium rating, heat in combustible in gas, percentage of heat in coal after firing.

	Bridge wall.	Top combustion chamber.	Flue.
Tar	1	2	.....
Soot	9	16	.....
Gas	6	11	0
Total	16	29	.....

It is obvious that these samples were taken from different streams of gas, as more combustible was apparently present on leaving the combustion chamber than on entering it.

Before firing at the high rate, the total heat loss percentage of the heat in the coal at the bridge wall was 0.4 per cent in the tar, 1.7 per cent in the soot, and none in the gas. No samples of gas were taken from the gas entering the mixing chamber or leaving the combustion chamber after firing and the tar and soot contents per unit volume of the gas leaving the chamber were about the same as those taken at the lower ratings before firing.

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More tar and soot would have been burned had all the air been admitted into the furnace instead of entering the stream of gases through leakage after leaving the furnace; such intermingling of all the air with the gases in the furnace would have raised the furnace temperature, which in turn would have enabled the gases to cool more rapidly in passing over the heating surface.

The dilution of the products of combustion after leaving the furnace by air from leaks has already been shown by temperature measurements; it is shown also from the composition of the gases. For the tests just mentioned, the air present per pound of carbon in the gases is shown in the table below:

Dilution of gases with air from leaks.

Rate	Pounds of air per pound of carbon in gas in its path from furnace to exit.					
	Before firing.			After firing.		
	Leaving furnace.	Leaving combustion chamber.	Leaving boiler.	Leaving furnace.	Leaving combustion chamber.	Leaving boiler.
Low	11.8	14.5	25.2	20.1	23.4	29.2
Medium	.....	.....	.....	18.1	19.9	39.6
High	15.4	18.6	26.9	.....	.....	.....

This table shows that 46 to 69 per cent of the total air entered the furnace, 4 to 12 per cent joined the gases in the combustion chamber, and the remaining 19 to 50 per cent joined the gases on their way from the combustion chamber to the boiler exit. Here again, however, are figures that are not to be taken too literally, for the samples of gas from the combustion chamber and furnace possibly contained less air than the average gas leaving the furnace or combustion chamber; nevertheless, it is obvious that considerable quantities of air passed into the boiler from leaks.

COMPOSITION OF GAS IN THE COMBUSTION CHAMBER AND LEAVING THE FURNACE.

Samples of gas were taken from the interior of the combustion chamber at the three points in the vertical transverse plane shown in Figures 17 and 18. Two of these points (C_1 and C_3) were on a vertical center line of the boiler; the upper point C_1 was in the main stream of the gas as it moved from over the bridge wall through the central vertical slot to the top pass, and C_3 was below C_1. Point C_2 was near the side of the combustion chamber, and gases entering the combustion chamber through the central slot had to turn to the side before reaching C_2.

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All of the samples of gas taken from the interior of the combustion chamber were drawn through small pipes, which were not water-cooled because there was no means of inserting the larger water-cooled pipe in the combustion chamber; and the combustible gases passing through the pipe must have continued to burn to some extent on their way to the collecting bottle. Consequently, the samples collected from the combustion chamber contained less

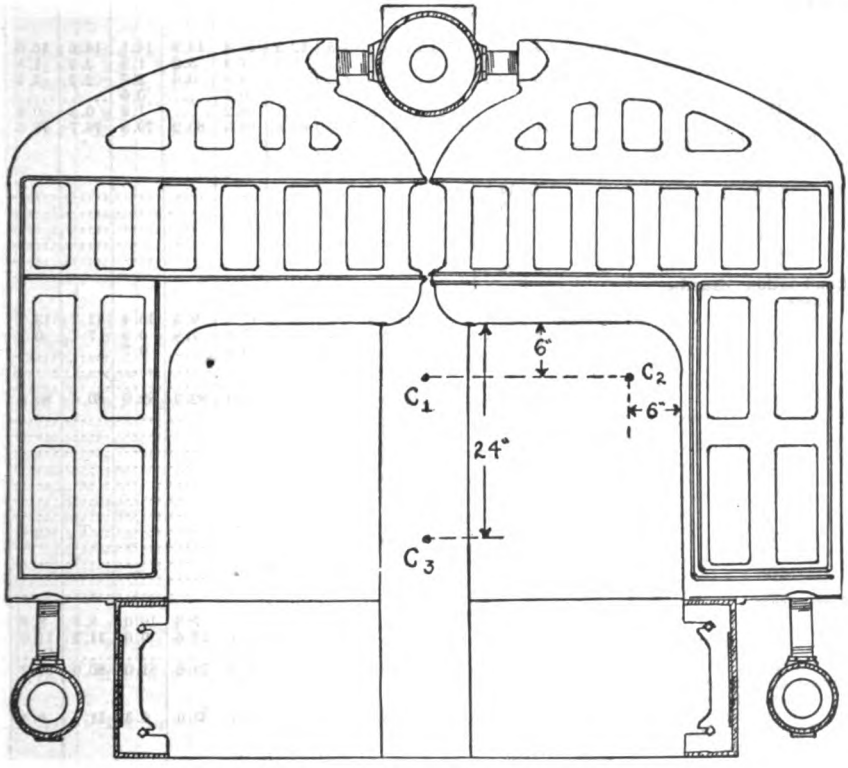

FIG. 17.—Rear elevation of combustion chamber, showing positions of gas samplers.

combustible gas than those entering the sampling tubes at C_1, C_2, and C_3.

Table 9 summarizes the composition of the samples of gases taken from the furnace and combustion chamber.

In the first four columns of the table are analyses of the gases taken during tests 8 and 8A with anthracite.

At the time samples for test 8 were taken the fuel bed was evidently compact, with no air channels, and little air was admitted over the fuel-bed, as the gas leaving the bottom of the opening from the furnace to the combustion chamber, both before and after firing, contained so much combustible gas that its chemical energy represented 38 per

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TABLE 9.—*Composition of gases leaving the furnace*

Kind of fuel	Anthracite.				Coke.		Bituminous.					
Trial number	8		8A		14	2	10E		11E		11E	
Before or after firing	B. F.	A. F.	B. F.	A. F.	B. F.	A. F.	B. F.	A. F.	B. F.	A. F.	B. F.	A. F.
Coal fired per hour, pounds.	385	.....	487	.....	513	208	360	.....	450	.....	450	.....
Furnace gases:												
Bottom of opening into mixing chamber—												
CO_2	11.3	8.4	16.7	17.4	17.6	13.5	12.3	13.4	13.9	14.1	16.6	16.0
O_2	0.2	.....	2.1	1.9	1.8	4.2	6.9	4.4	5.3	1.8	2.2	1.8
CO	14.0	17.5	0.7	0.7	1.2	4.0	.....	0.9	0.6	2.7	2.2	3.3
CH_4	0.5	0.8	.....	.....	.....	.....	.....	0.3	.....	0.9	.....	.....
H_2	1.5	5.2	.....	.....	.....	0.3	.....	0.2	.....	1.0	0.3	0.4
N_2	72.5	68.1	80.5	80.0	79.4	78.0	80.8	80.8	80.2	79.5	78.7	78.5
Top of opening into combustion chamber—												
CO_2	.....	.....	14.1	.....	.....	.....	.....	.....	.....	.....	.....	.....
O_2	.....	.....	5.6	.....	.....	.....	.....	.....	.....	.....	.....	.....
CO	.....	.....	0.8	.....	.....	.....	.....	.....	.....	.....	.....	.....
CH_4	.....	.....	0.0	.....	.....	.....	.....	.....	.....	.....	.....	.....
H_2	.....	.....	0.0	.....	.....	.....	.....	.....	.....	.....	.....	.....
N_2	.....	.....	79.5	.....	.....	.....	.....	.....	.....	.....	.....	.....
Combustion chamber gases:												
C_1—CO_2	16.4	16.4	.....	.....	14.3	14.2	10.1	12.9	9.3	16.4	11.7	13.1
O_2	2.8	2.1	.....	.....	6.1	5.3	9.2	5.4	7.8	0.9	7.7	6.1
CO	0.3	0.5	.....	.....	.....	.....	.....	0.4	.....	0.7	.....	.....
CH_4	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
H_2	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
N_2	80.5	81.0	.....	.....	79.6	80.5	80.7	81.3	82.9	82.0	80.6	80.8
C_2—CO_2	.....	.....	.....	.....	14.0	.....	.....	.....	.....	.....	.....	.....
O_2	.....	.....	.....	.....	6.6	.....	.....	.....	.....	.....	.....	.....
CO	.....	.....	.....	.....	0.2	.....	.....	.....	.....	.....	.....	.....
CH_4	.....	.....	.....	.....	0.0	.....	.....	.....	.....	.....	.....	.....
H_2	.....	.....	.....	.....	0.0	.....	.....	.....	.....	.....	.....	.....
N_2	.....	.....	.....	.....	79.2	.....	.....	.....	.....	.....	.....	.....
C_3—CO_2	.....	.....	.....	.....	13.2	.....	.....	.....	.....	.....	.....	.....
O_2	.....	.....	.....	.....	7.4	.....	.....	.....	.....	.....	.....	.....
CO	.....	.....	.....	.....	0.0	.....	.....	.....	.....	.....	.....	.....
CH_4	.....	.....	.....	.....	0.0	.....	.....	.....	.....	.....	.....	.....
H_2	.....	.....	.....	.....	0.0	.....	.....	.....	.....	.....	.....	.....
N_2	.....	.....	.....	.....	79.4	.....	.....	.....	.....	.....	.....	.....
Flue gases:												
CO_2	12.0	11.8	9.4	10.2	10.4	9.0	7.8	9.6	7.8	10.0	8.8	8.8
O_2	7.6	7.6	11.4	10.2	10.6	11.6	12.6	9.6	12.6	9.0	11.2	11.0
CO	0.0	0.2	0.2	0.2	.....	0.1	0.0	0.0	.....	.....	.....	.....
N_2	80.4	80.4	79.0	79.4	79.0	79.3	79.6	80.8	79.6	81.0	80.0	80.2
Excess air, per cent:												
Bottom of opening into mixing chamber	1.0	0.0	10.8	9.8	9.3	25.6	47.3	25.7	33.0	9.3	11.7	9.4
Top of opening into combustion chamber	.....	.....	36.0	.....	.....	.....	.....	.....	.....	.....	.....	.....
In combustion chamber—												
C_1	15.0	10.7	.....	.....	40.5	33.1	75.0	33.3	54.7	4.3	56.1	39.6
C_2	.....	.....	.....	.....	45.6	.....	.....	.....	.....	.....	.....	.....
C_3	.....	.....	.....	.....	53.9	.....	.....	.....	.....	.....	.....	.....
In stack	55.2	55.2	118.6	93.5	101.8	123.4	147.2	80.8	147.2	71.8	111.3	106.6
Per cent of heat of fuel in gas:												
Bottom of opening	38.1	54.4	2.3	2.2	4.0	16.0	.....	7.7	2.3	20.4	7.3	10.5
Top of opening	.....	.....	3.0	.....	.....	.....	.....	.....	.....	.....	.....	.....
C_1	1.0	1.7	.....	.....	.....	.....	.....	1.7	.....	2.3	.....	.....
C_2	.....	.....	.....	.....	0.9	.....	.....	.....	.....	.....	.....	.....
C_3	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
In flue gases	.....	1.0	1.2	1.1	.....	0.7	.....	.....	.....	.....	.....	.....

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and in the combustion chamber, per cent by volume.

Bituminous—Continued.										Coke breeze.					
13E		15C		12		12		12		3SA.		4SA.		4SA.	
B. F.	A. F.	B. F.	A. F.	B. F.	A. F.	B. F.	A. F.	B. F.	A. F.	B. F.	A. F.	B. F.	A. F.	B. F.	A. F.
360	.....	252	.....	159	.....	.....	.....	.....	.....	265	.....	176	.....	.....	.....
18.1	16.0	13.0	14.5	6.5	12.3	6.6	12.9	9.4	13.4	13.5	15.2	12.9	14.2	10.6	13.0
1.5	2.4	7.9	3.1	13.9	2.5	14.0	2.4	10.1	2.0	7.1	3.6	7.7	0.9	9.2	5.3
1.6	2.1	.....	3.2	0.1	3.3	0.2	2.9	0.2	4.1	.....	1.2	.....	5.1	.....	1.0
.....	.....	.....	.....	.....	1.3	.....	0.9	.....	0.3	.....	0.2	.....	1.0	.....	.....
0.1	0.2	.....	0.8	.....	0.8	.....	1.5	.....	1.0	.....	0.1	.....	0.2	.....	0.4
78.7	79.3	79.1	78.4	79.5	79.8	79.2	79.4	80.3	79.2	79.4	79.7	79.4	78.6	80.2	80.3
.....	.....	.....	.....	.....	14.2	.....	9.0	.....	14.2	.....	.....	12.6	16.2	7.8	10.0
.....	.....	.....	.....	.....	3.3	.....	10.5	.....	1.4	.....	.....	8.1	1.3	11.8	8.8
.....	.....	.....	.....	.....	1.3	.....	0.0	.....	2.2	.....	.....	0.0	1.4	0.0	0.0
.....	.....	.....	.....	.....	0.0	.....	0.0	.....	0.4	.....	.....	0.0	0.4	0.0	0.0
.....	.....	.....	.....	.....	0.4	.....	0.0	.....	0.0	.....	.....	0.0	0.0	0.0	0.0
.....	.....	.....	.....	.....	80.8	.....	80.5	.....	81.8	.....	.....	79.3	80.7	80.4	81.2
11.8	12.1	13.4	9.2	.....	10.6	5.7	6.1	8.7	11.3	9.2	11.2	.....	12.2	.....	5.0
8.0	7.2	6.6	9.3	.....	7.3	15.0	13.7	10.9	5.7	11.1	8.4	.....	5.0	.....	13.1
.....	.....	.....	2.9	.....	0.4	.....	.....	.....	2.0	.....	0.3	.....	2.7	.....	0.5
.....	.....	.....	.....	.....	0.1	.....	.....	.....	0.2	.....	.....	.....	0.2	.....	.....
.....	.....	.....	.....	.....	0.1	.....	.....	.....	0.1	.....	.....	.....	0.2	.....	0.3
80.2	80.7	80.0	78.6	.....	81.5	79.3	80.2	80.4	80.7	79.7	80.1	.....	79.7	.....	81.1
.....	.....	.....	.....	6.5	.....	.....	.....	.....	.....	.....	.....	.....	7.3	.....	.....
.....	.....	.....	.....	14.0	.....	.....	.....	.....	.....	.....	.....	.....	10.9	.....	.....
.....	.....	.....	.....	0.0	.....	.....	.....	.....	.....	.....	.....	.....	2.7	.....	.....
.....	.....	.....	.....	0.0	.....	.....	.....	.....	.....	.....	.....	.....	0.0	.....	.....
.....	.....	.....	.....	0.0	.....	.....	.....	.....	.....	.....	.....	.....	1.2	.....	.....
.....	.....	.....	.....	79.5	.....	.....	.....	.....	.....	.....	.....	.....	77.9	.....	.....
.....	.....	.....	.....	.....	8.5	.....	8.5	.....	.....	.....	.....	.....	4.6	.....	.....
.....	.....	.....	.....	.....	8.4	.....	9.5	.....	.....	.....	.....	.....	14.1	.....	.....
.....	.....	.....	.....	.....	1.6	.....	0.8	.....	.....	.....	.....	.....	1.7	.....	.....
.....	.....	.....	.....	.....	0.8	.....	0.3	.....	.....	.....	.....	.....	0.0	.....	.....
.....	.....	.....	.....	.....	0.3	.....	0.1	.....	.....	.....	.....	.....	0.2	.....	.....
.....	.....	.....	.....	.....	80.4	.....	80.8	.....	.....	.....	.....	.....	79.4	.....	.....
10.0	9.8	8.4	3.6	4.8	8.4	5.6	8.0	6.6	7.4	5.0	5.0	.....	7.6	5.6	6.0
12.2	9.8	11.6	8.2	16.0	9.0	15.6	10.4	13.6	9.8	15.4	15.0	.....	11.0	15.6	14.0
.....	.....	.....	2.8	.....	1.6	.....	1.0	.....	2.6	0.4	0.2	.....	2.0	.....	0.4
77.8	81.4	80.0	80.4	79.2	81.0	78.8	80.6	79.8	80.2	79.2	79.8	.....	79.4	78.8	79.6
7.7	12.8	60.2	16.6	192.2	13.3	198.6	12.8	89.9	10.5	50.7	20.4	57.5	4.5	76.0	33.0
.....	.....	.....	.....	.....	18.1	.....	96.3	.....	6.8	.....	.....	62.4	6.3	123.3	68.8
60.0	50.5	45.0	80.2	.....	50.7	249.9	179.7	104.1	38.2	110.0	65.1	.....	30.9	.....	149.5
.....	.....	.....	.....	196.4	.....	.....	.....	.....	.....	.....	.....	.....	111.1	.....	.....
.....	.....	.....	.....	.....	64.7	.....	79.3	.....	.....	.....	.....	.....	201.0	.....	.....
128.9	82.8	119.9	62.2	316.8	71.8	292.0	94.3	178.6	85.0	272.1	241.3	.....	108.9	292.0	195.4
4.7	7.0	.....	12.4	0.8	26.7	1.6	24.1	1.2	18.8	.....	6.4	.....	22.0	.....	5.3
.....	.....	.....	.....	.....	6.1	.....	.....	.....	11.4	.....	.....	.....	7.8	.....	.....
.....	.....	.....	13.2	.....	4.0	.....	.....	.....	11.2	.....	1.4	.....	12.4	.....	7.7
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	20.7	.....	.....
.....	.....	.....	.....	.....	22.3	.....	10.6	.....	.....	.....	.....	.....	15.9	.....	.....
.....	.....	.....	13.5	.....	8.9	10.6	6.1	.....	14.4	4.1	2.1	.....	11.0	.....	3.3

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cent of the heat in the coal before firing and 54 per cent of that after firing. And as only 1 to 2 per cent of the heat energy of the coal was present as combustible gas in the combustion-chamber sample, apparently almost as much heat energy was liberated in the combustion chamber as was liberated in the furnace. But this does not necessarily apply to the whole gas stream, as the remainder of the stream passing from the furnace probably had a lower calorific value. Nor is it likely that the sample taken from the combustion chamber exactly represented the average composition of the gas there, and, as stated before, the combustible gas burned to some extent in passing through the sampling tube.

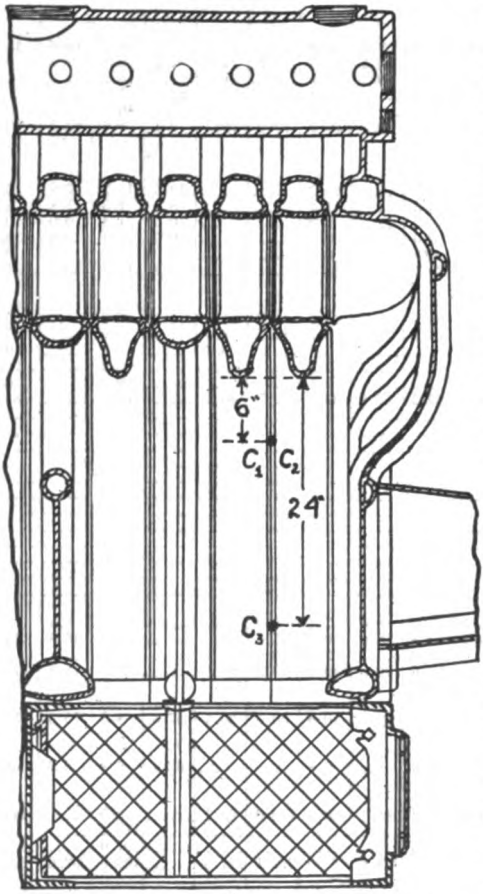

FIG. 18.—Side elevation of combustion chamber, showing positions of gas samplers.

The samples of gas taken from the combustion chamber before and after firing during test 8 contained 15 and 11 per cent excess air, and from the flue leaving the boiler 55 per cent excess air. Most of this additional air probably leaked into the the combustion and mixing chambers through cracks.

The composition of two other samples taken while burning anthracite during test 8A shows that much less combustible was present in the gases leaving the furnace than when the samples were taken during test 8; about the same proportion of combustible gas was present at the top as at the bottom of the opening from the furnace, and about twice as much free oxygen was present at the top of the opening as at the bottom. The quantity of combustible in the gas was less in these samples than in those taken during test 8, because more air was admitted through the fire doors; that is to say, the gases were burned almost completely in the furnace when the samples were taken during test 8A, whereas in test 8 a large quantity

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of the gases were burned in the combustion chamber with air that entered mostly by leakage. The admission of more air into the furnace during test 8A than in test 8 is shown by the composition of the flue-gas samples from test 8A, which contained about twice as much excess air.

It is clear from the composition of the gases leaving the furnace collected during test 8A that enough air could be admitted to the furnace through the fire doors and mixed with the gases to burn almost completely the combustible gases rising from the fuel bed; but if all the air required to burn the gases were brought in through the fire doors, the air leaking into the combustion chamber merely diluted and cooled the gases.

While samples were being taken in test 8, not enough air entered the furnace to burn the gases and the air that leaked into the combustion chamber was used to burn the gases instead of merely to dilute and cool them. Had no air leaked into the chamber, the gases would have been burned in the furnace by air admitted through the fire doors and the efficiency would have been higher because the gases would have burned earlier in their path and therefore would have reached a higher temperature.

In Table 9 the composition of the special samples taken when burning anthracite precede the composition of the special samples taken when burning coke during tests 14 and 2.

During test 14 the sample of gas taken from the furnace exit before firing contained little carbon monoxide and only one of the three samples taken from the combustion chamber contained any of this gas. The samples from the three points C_1, C_2, and C_3 had practically the same composition, excepting that from point C_2, nearer the side of the combustion chamber, which contained 0.2 per cent carbon monoxide, whereas the other two samples (from C_1 and C_3) contained none.

In test 2 the sample from the furnace exit after firing contained 4 per cent carbon monoxide, which represented 16 per cent of the heat energy in the fuel. None of this gas was present in the corresponding sample taken from the combustion chamber, although a trace was present in the flue gas.

Eight sets of samples were taken while firing bituminous coal. In the table the letter E after the number of the test shows that the test was an extra one run solely to observe the composition of the gases and the density of the smoke; and the letter C denotes that the coal was fired by the coking method.

This series of samples proves that much more combustible gas and, with the exception of one pair of samples, less free oxygen, were present in the samples taken as the gases left the furnace, just after firing, than were present just before firing.

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The samples taken during test 10E, 11E, and 13E show that the combustible gases had burned before reaching the flue-gas exit; but during test 15C the percentage of heat of the coal present in the gases after firing remained practically constant from the furnace to the flue-gas exit; and after firing during test 12, considerable unburned gases remained in the flue gas in spite of the presence of a good supply of free oxygen in the samples taken both from the combustion chamber and the flue. The combustible content of the sample taken from the lowest sampling point in the combustion chamber was much higher than that of the one taken from the higher sampling point above it, in spite of a large free oxygen content, probably because of the lower gas velocity and poorer mixing at this part of the stream.

The set of samples taken during test 4SA, after firing, from points C_1, C_2, and C_3 in the combustion chamber showed that there was less combustible gas present at the top in the center than at the sides or bottom, possibly because of the higher velocity and better mixing of the gases at the center of the stream.

The special samples of gas as a whole show (1) the good design of the mixing and combustion chamber, wherein the large quantity of combustible gases leaving the furnace after firing was burned rapidly; (2) the leakage of air into the combustion chamber and flues which reduced the efficiency of the boiler; (3) the presence of far more combustible gas in the furnace exit after firing than before firing; and (4) that without opening the fire-door dampers enough just after firing, half of the combustion may remain to be completed in the mixing and combustion chambers.

SMOKE.

The density of the smoke issuing from the stack was estimated by comparing it with a Ringelmann smoke chart. Table 10 shows the densities at various rates of combustion.

In the third column of the table, S denotes the spreading and C the coking method of firing. The figures give no conclusive evidence that less smoke will be produced in firing by the coking method. The smoke emission with spreading and coking methods for two firing periods are shown diagrammatically in Figure 19.

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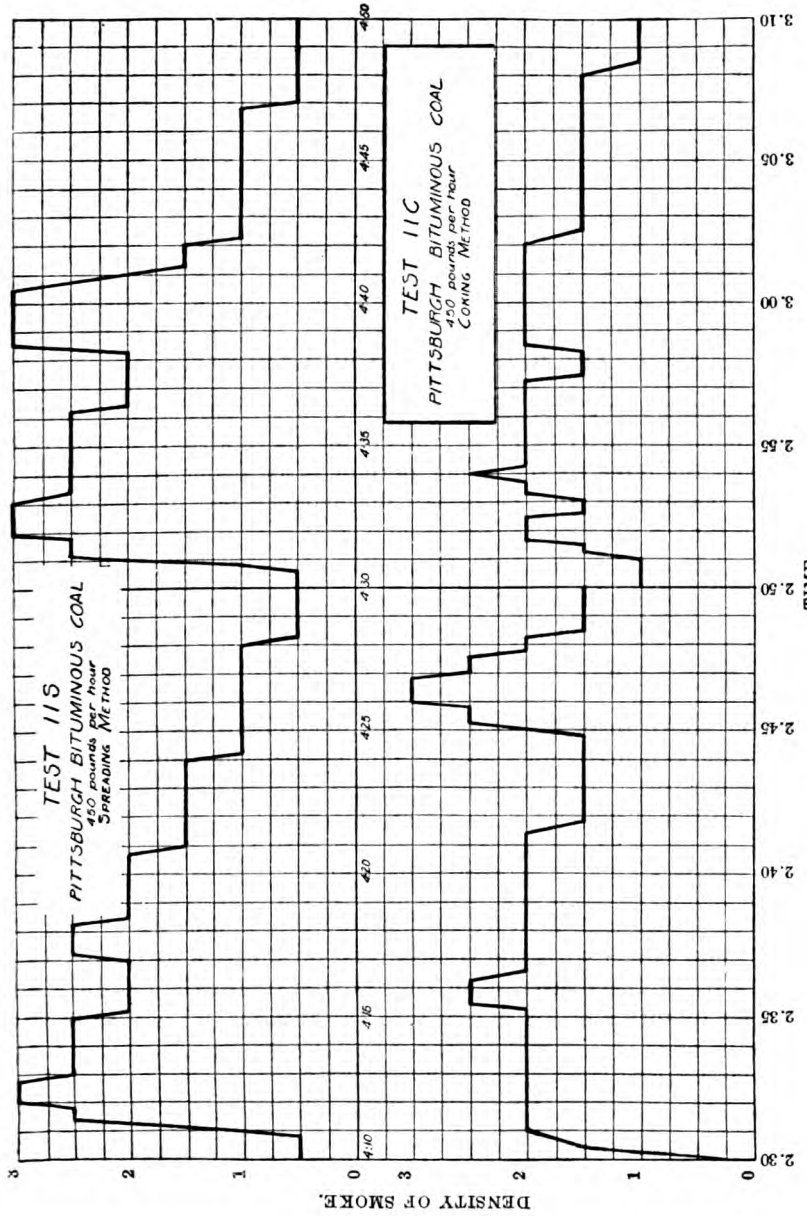

FIG. 10.—Smoke emission after firing by coking method and by spreading method.

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TABLE 10.—*Smoke emission.*

Test. No.	Fuel.	Method of firing.	Rate of firing, pound per hour.	Coal per firing, pound.	Average interval between firings, minutes.	Duration of smoke readings, minutes.	Flue-gas temperature, °F.	CO_2, per cent.	CO, per cent.	Excess air, per cent.	No. 1, smoke, per cent.
12	Bituminous.....	S.	130	167	77	230	405	7.2	0.4	146	22.22
12	.....do.....	C.	150	150	60	120	467	7.7	0.7	120	29.31
17	.....do.....	S.	150	150	50	100	388	6.4	0.1	187	17.35
2E	.....do.....	C.	225	68	18	87	594	10.3	0.5	78	30.85
15	.....do.....	C.	225	150	40	235	564	9.0	1.0	89	32.00
E	.....do.....	S.	263	153	35	205	556	10.4	1.6	52	41.20
1E	.....do.....	C.	270	72	16	98	565	7.5	0.1	134	49.80
10E	.....do.....	S.	360	150	25	100	536	8.4	0.04	110	35.80
13E	.....do.....	C.	360	150	25	100	636	9.6	0.0	102	27.95
11E	.....do.....	S.	450	150	20	60	636	8.9	0.0	98	36.00
11E	.....do.....	C.	450	150	20	80	673	8.0	0.0	130	34.91
1SA	Bituminous and coke breeze....	S.	168	157	54	585	452	6.5	0.2	193	12.39
2SA	.....do.....	S.	368	154	25	521	571	7.8	0.1	138	14.96
3SA	.....do.....	S.	265	155	36	460	464	5.2	0.1	258	13.43
4SA	.....do.....	S.	176	154	53	831	382	6.7	0.2	172	16.57

DRAFT REQUIRED TO BURN FUELS.

More smoke was given off immediately after firing by the spreading method than after firing by the coking method; but more smoke was given off later in the firing period, after firing by the coking method, because of the necessary disturbance of the fuel bed in preparing it for the new charge of coal.

As the excess air increased, the smoke generally decreased, though more smoke was observed, test 1E, with the high excess-air content of 134 per cent than in any other test. This high density of smoke, however, was largely caused by frequent disturbance of the fuel bed.

During short tests 1E and 2E smaller quantities of coal were charged at a firing, but this did not reduce the smoke emission. In firing mixtures of bituminous coal and coke breeze the smoke was considerably less than when firing the former alone.

TOTAL DRAFT.

Figure 20 shows the draft in the flue where the gases left the boiler. The drafts with the coke-breeze mixtures were higher than with the other fuels because of the greater fuel-bed resistance and the larger quantity of air drawn into the furnace. The drafts with anthracite were greater than those with coke on account of the greater fuel-bed resistance.

The curve showing the drafts for bituminous coal crosses the curves for anthracite and coke; it lies above them at the lower rates of steaming because the air supply was greater, and lies below them at the higher rates because the air supply was less. The isolated point above the bituminous coal curve is for test 16 with the abnormally

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large air supply, and shows how an increase in the air supply materially increases the required draft.

ASH-PIT DRAFT.

The draft used to draw the air into the ash pit, shown in item 22, Table 1 (p. 12) was increased at times by partly closing the ash-pit door in order to increase the draft over the fuel bed and thus draw more air over it.

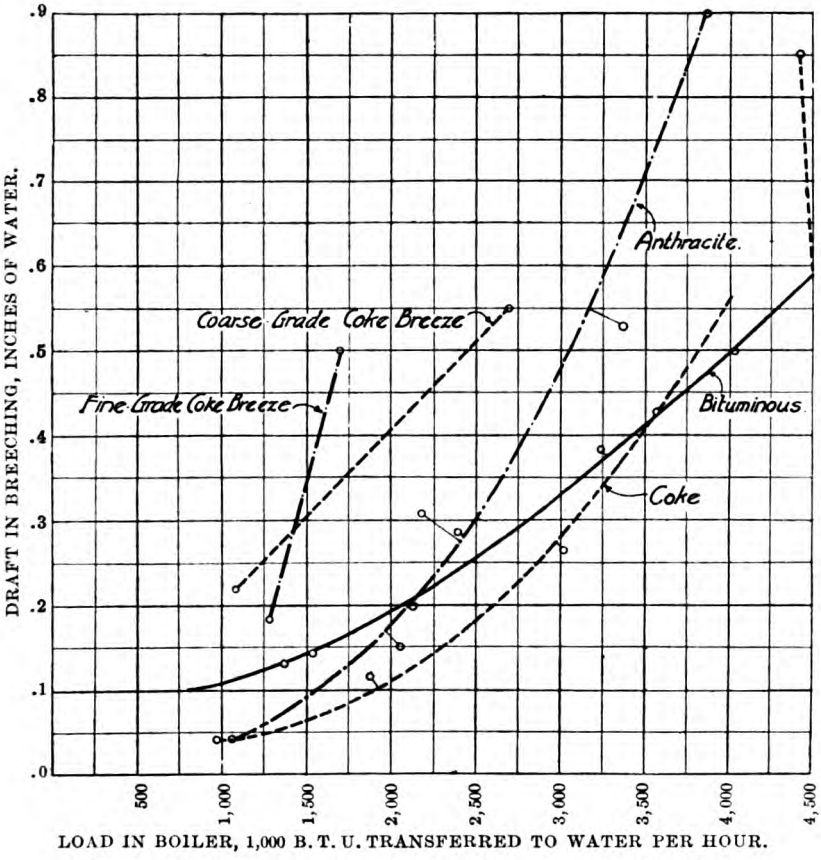

FIG. 20.—Draft in breeching at different rates of steaming with the several fuels.

DRAFT DROP THROUGH GRATE AND FUEL BED.

Figure 21 shows the difference between the draft measured above the fuel bed and below the grates at various rates of combustion and with fixed and shaking grate bars. Only a little more draft was required to burn coke than bituminous coal; considerably more to burn anthracite and the mixture of the coke breeze and bituminous coal; more was required to burn the fuels on fixed grates than on shaking grates; and more was needed to burn bituminous coal by the coking than by the spreading method.

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The curve representing the draft difference when burning coke on shaking grates shows the draft in the furnace to be less than that in the ash pit when less than 5.6 pounds of coke was burned per square foot of grate surface per hour, and most of the curves shown in Figure 21, if continued downward, would cut the axis of zero difference of draft for a positive rate of combustion, showing that at low rates of combustion the furnace draft is less than the ash-pit draft. To explain this a concrete example follows:

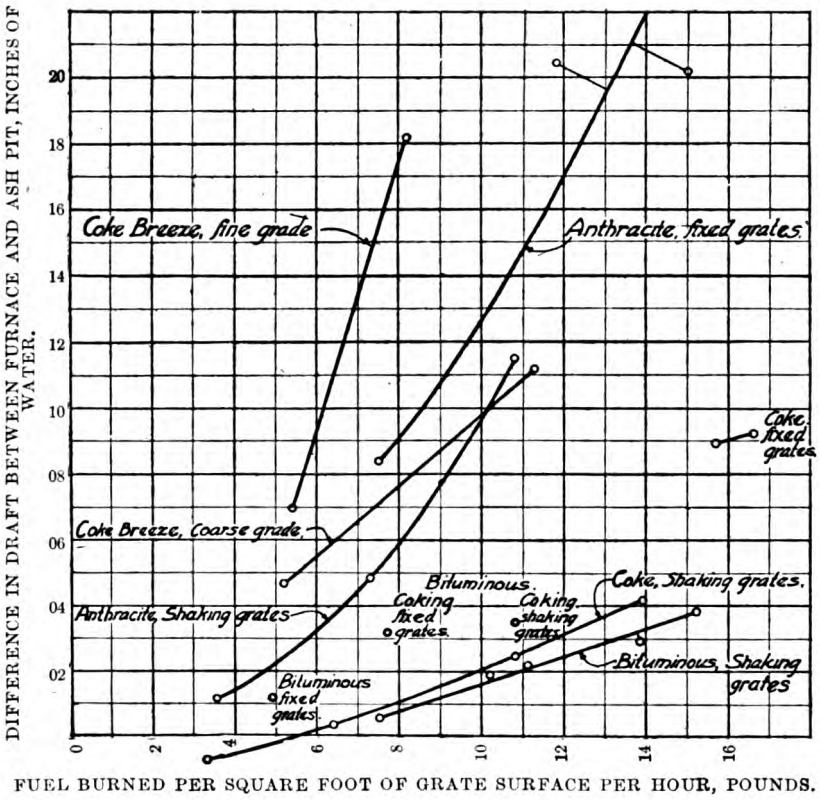

FIG. 21.—Difference in draft between furnace and ash pit at different rates of combustion with the several fuels and with fixed and with shaking grates.

During test 1, when burning coke, the mean draft measured above the fuel bed was 0.017 inch of water and the draft below the fuel bed 0.024 inch; so it seems at first sight that gas was flowing through the fuel bed from a space of low pressure to one of high pressure. Obviously this did not happen, and the paradox is easily explained.

The two drafts were measured at approximately 2 feet apart, vertically, and showed therefore the difference in pressure between the gas inside and air outside at the levels where they were measured. Had the density of the gas inside been equal to the density of the air outside, the difference between the two draft readings would

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have represented the net pressure acting on the vertical column of gas to force it through the fuel bed. But the gas inside was at a mean temperature of about 1,300° F., and the air outside at 75° F., so that, assuming the density of the gas inside at normal temperature and pressure to have been 4 per cent greater than that of air, the ratio of the density of the gas at 1,300° F. to the air at 75° F. was $\frac{(460+75)\times 1.04}{1300+460}=0.3$ approximately. Let the pressure of the air at the level of measuring the furnace draft be denoted by p pounds per square foot, or h inches of water, and assume that the density of the air was the same at the level 2 feet below where the ash-pit draft was measured: Then, since the density of the air is 0.074 pound per cubic foot, the air pressure at the lower level will be $(p+2\times 0.074)$ $=(p+0.148)$ pounds per square foot, or $\frac{1}{5.2}$ $(p+0.148)$ inches of water $=h+0.028$.

The pressure of the gas in the furnace was 0.017 inch of water, and in the ash pit 0.024 inch less than the air at the same levels; thus the actual pressure acting upward on the column of gas 2 feet high was

$$(h+0.028-0.024)-(h-0.017)=0.021 \text{ inch of water.}$$

This pressure was used partly to overcome the frictional flow, partly to increase the velocity of the gases, and partly to support the 2-foot column of gas. As the 2-foot column of air exerted a pressure of 0.028 inch of water, and the density of the gas was 0.3 that of the air, the 2-foot column of gas exerted a pressure of $0.3\times 0.028=$ 0.008 inch of water. Therefore the net pressure used to force the gas through the fuel bed and increase its velocity was $0.021-0.008$ $=0.013$ inch of water.

This calculation is not exact, because the mean density of the gas in and above the fuel bed is not known precisely; but it suffices to explain a common occurrence when fuels are burned at a low rate, one may easily be observed in a domestic furnace by closing the damper in the flue and opening the ash-pit door, when gases will leave the furnace through any openings near its top. Evidently the pressure inside must be greater than that outside at the same level at the top of the furnace, although the pressure of the air inside the ash pit is less than that of the air outside at the ash-pit level.

DRAFT DROP BETWEEN FURNACE AND GAS EXIT FROM BOILER.

Figure 22 shows the draft required to draw the flue gases from the furnace through the mixing chamber, combustion chamber, and flues to their exit from the boiler. It is plotted on a base representing the pounds of flue gas flowing from the boiler per hour.

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Experiments have shown that a gas flowing through a channel, under nearly constant pressure, meets a frictional resistance approximately proportional to the absolute temperature of the gas and the square of the weight of gas flowing per unit of time. The curve shown in Figure 22 was constructed from the equation

$$D = 465 \times 10^{-12} \times F^{2.3}$$

where D represents the drop in draft, in inches of water, and F represents the pounds of flue gas per hour.

The exponent 2.3 is greater than 2 because the temperature of the flue gas increased as the flow increased. Most of the points represent-

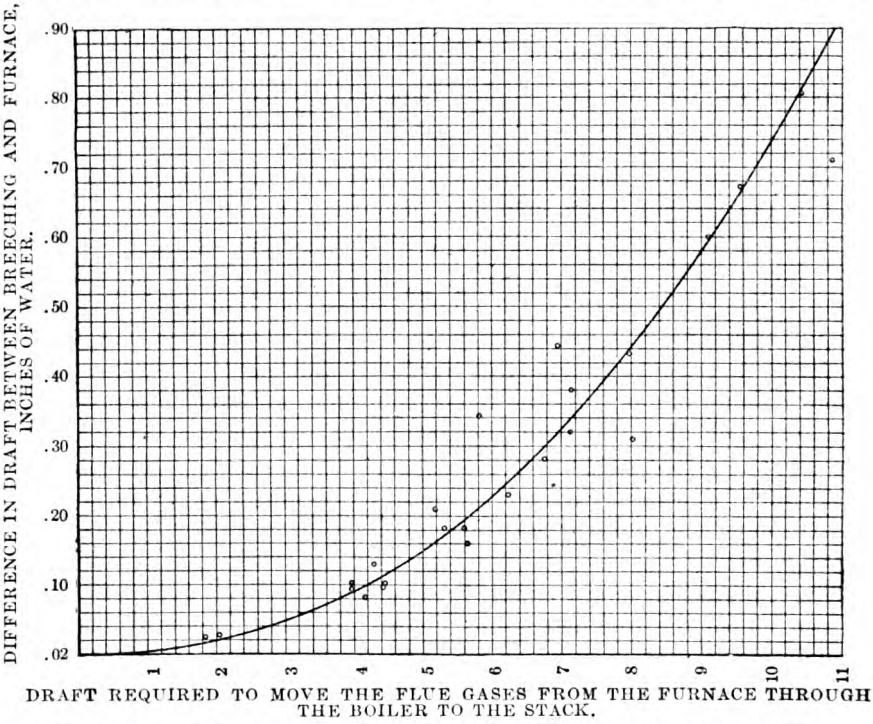

FIG. 22.—Draft required to move the flue gases from the furnace, through the boiler, to the stack.

ing the tests lie fairly close to the curve; the two points lying well above it, near the center, are for two bituminous coal tests in which the excess air was low and the mean temperature of the gas in the boiler flues was high.

The point well below the upper part of the curve is for test 14A, with coke, and the point well below the center of the curve is for test 3SA with a mixture of coke breeze and coal. No valid explanation for the position of these points is evident.

The draft in some of the tests was also measured at the top of the combustion chamber and at the front of the top pass. The total

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frictional resistance between the furnace and the flue leaving the boiler was divided proportionally as follows: Thirty-four per cent between the furnace and combustion chamber exit, 22 per cent across the top pass, and 44 per cent across the bottom side passes.

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